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DYNAMIC EQUIPMENT POLICY

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DYNAMIC EQUIPMENT POLICY

by

GEORGE TERBORGH

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III

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FOREWORD

The "crisis of production" in which some of the older industrial countries of Europe now find themselves is attributable only in part to the physical devastation and economic dislocation of war. There is a growing realization that it is due also—and in some cases predominantly—to a long-continued neglect of the physical facilities of production. Too frequently these facilities have been allowed to sink into obsolescence and decrepitude, with the inevitable penalty of high costs, wasted manpower, and inadequate output. They have become stranded in a technological backwater.

In earlier times such technological stagnation was regarded with tolerance, if not indifference, by the governments concerned, but no longer. Now that increased production has become a condition of the survival of these governments, and even of the social and political order itself, it is as clear as day that industrialists will no longer be permitted to drowse along unmolested a generation behind the times. They must modernize voluntarily or they will eventually be modernized by the state. Already several governments are studying the problem.

Here in the United States the situation is less serious, mainly because our industrialists, on the whole, have done a better job of keeping their methods and equipment up to date. Certainly the government has not yet begun to prod them for efficiency as it has elsewhere. That it is becoming aware of the problem for the future, however, is made evident by the recent report of the President's Scientific Research Board, which observes:

> The future is certain to confront us with competition from other national economies of a sort we have not hitherto had to meet. Many of these will be state-directed in the interest of national

policies. Many will be supported by new, highly efficient industrial plant and equipment—by the most modern technology. The destructiveness of the recent war makes it inevitable that much of Europe, in rebuilding its factories, will soon possess an industrial plant more modern than ours of today.

What may be the significance of this fact can be illustrated by the unhappy experience of England during our lifetime. Since the turn of the century, the British have been paying, in terms of technological obsolescence, the penalty for their early industrial leadership. Particularly in the basic industries, British facilities and technology were older and less efficient than their German counterparts. The balance of power in Europe was upset primarily as a result of this fact, and the world was plunged into two devastating wars. Today, one of the most serious long-term problems still facing the British Government is the modernization of industrial facilities.

I mention these developments here, anticipating a later discussion, to emphasize the timeliness of the whole subject of equipment policy. We are certain to hear a great deal of it in the years ahead. It is an appropriate moment, therefore, for a fundamental rethinking of theory in this field, and a reappraisal of practice accordingly. This is the task essayed by the present study.

It is fitting that this investigation should be conducted by the Machinery and Allied Products Institute, a federation of trade associations in the industrial equipment field. That a dynamic equipment policy in American industry is of vital interest to machinery manufacturers goes without saying. If, as we believe, industry is generally laggard in the replacement of its facilities and can accelerate their turnover to its own advantage, the development and dissemination of sound standards of practice should expand the demand for new equipment, to the benefit of its producers.

While the significance of the study to machinery manufacturers is thus quite obvious, this is secondary, in our judgment, to its significance for the country at large. A dynamic equipment policy means a dynamic economy. It means a more rapid increase in the standard of living and in national well-being. It means a better competitive position in inter-

national trade. It means greater strength and security as a world power. The Institute has no hesitation, therefore, in bespeaking the attention of the disinterested reader. It does not believe that the importance of the study for the economy as a whole is in any way qualified or impaired by its special significance for the producers of machinery. The special and the general interests are here in harmony.

The present work, I have said, is an attempt to rethink fundamentally the underlying theory of equipment policy. I may add— if it is proper to anticipate the discussion to this extent—that it is an attempt to integrate into this theory a recognition of the phenomenon of obsolescence, strangely ignored (as to *future* obsolescence at least) by existing theory. It is thus a piece of intellectual pioneering. As such it lays no claim to being the final word on the subject; indeed, it is hoped that one of its principal results will be the stimulation of fresh inquiry in the field and a further enrichment of our understanding in consequence.

While the book is primarily a theoretical analysis, I must not leave the impression that it is an exercise in theory for its own sake. Its guiding purpose, and its only reason for being, is the criticism, and through this the improvement, of equipment practice itself. This criticism runs throughout the work, engaging in its course an amazing, and even appalling, collection of errors and fallacies more or less prevalent in current practice. The proposals for improvement appear in the form of practical short cuts and rules of thumb satisfactorily consonant with the requirements of theory as developed in the course of the analysis. These practical suggestions are, indeed, the pay-off on the entire project.

Having characterized the book, let me offer some suggestions as to who should read it. The subject is inherently difficult and of necessity the analysis is also difficult. *This is not a work for the casual reader.* It demands close and patient application. On the other hand, there is nothing in the text that requires special training beyond a knowledge of simple arithmetic. (Two or three of the appendixes employ more

advanced mathematics, to be sure, but they are not essential). The only requisite, other than ordinary intelligence, is a genuinely serious interest in the subject. I commend the work, therefore, to everyone, regardless of professional background, whose interest is of this character.[1] This group should include many business executives responsible for the equipment policy of their enterprises, many students of engineering who look forward to this responsibility in the future, and a goodly number of economists and others concerned with the problem on broader grounds. I want especially to commend it to those who plan and direct engineering education in this country, because of my conviction that the important subject of equipment policy has long been sadly neglected by their institutions.

In closing let me add a word about the history of the project. The decision to inaugurate the study was made early in 1943, and the Institute published shortly thereafter two preliminary reports by its research staff, *The Short Pay-off in Machinery Replacements* and *Investment Earnings vs. Cost Savings in Machinery Replacement* (Research Memoranda Nos. 1 and 2). Before the work had progressed far, however, it was set aside in favor of a project deemed even more urgent, an analysis of the doctrines—or as it now appears, the mythology—of economic maturity. This undertaking was completed in 1945 with the publication of *The Bogey of Economic Maturity*, a book that has had already a profound influence on the thinking of economists and laymen alike. Since then the staff has been engaged, though with frequent interruptions, on the investigation reported here.[2] It represents, obviously, a major investment of time and effort, which the Institute is glad to contribute in a good cause.

[1] For those whose interest does not justify the close study required by the book itself, the Institute expects to release later a pamphlet embodying the main conclusions and recommendations but without the full analysis. Both versions have their place, of course, but it should be emphasized that only the book can yield a real understanding of the theory involved.

[2] One of these interruptions gave rise to an important and widely acclaimed study, *Depreciation Policy and the Postwar Price Level* (May, 1947); another, to an equally significant brochure on tax policy, *Capital Goods Industries and Tax Reform* (November, 1947); still another to an arresting analysis of industrial retardation in a foreign country, *Technological Stagnation in Great Britain* (January, 1948).

The author is our Director of Research, George Terborgh, whose recent contributions to the list of Institute publications include such outstanding works as *An Appraisal of the Fatalistic View of Capitalism* and *The Bogey of Economic Maturity*, already mentioned. As usual, he has been assisted by our Executive Committee and by a Special Committee appointed for the project. Both committees have reviewed the manuscript as written and have contributed their knowledge and experience, making the final result an official Institute product.

WILLIAM J. KELLY
President, MAPI

CHICAGO, ILL.
June, 1949

AUTHOR'S ACKNOWLEDGMENTS

As Mr. Kelly has indicated in his prefatory remarks, the project now brought to completion in the publication of this book has suffered numerous vicissitudes and has extended over a long period of time. He did not say, as he might well have done, that this period has been much longer than anyone expected or bargained for. There must have been times, indeed, when he wondered whether the whole thing was not a wild goose chase, and it is hard to believe that he did not occasionally restrain an impulse to terminate it forthwith. If he felt such misgivings, I never learned of them. In this long, arduous, and frequently exasperating undertaking, his patience has seemed inexhaustible. Certainly no author could ask for more unwavering support than I have enjoyed. It is a pleasure, therefore, to acknowledge first of all my profound obligation to Mr. Kelly.

To the members of the Executive Committee and the Special Committee on the project, all of whom have had the responsibility of reading the manuscript of this book in at least two versions, I extend my heartfelt gratitude. It has been an onerous task indeed, and I could pardon all of them for forswearing the subject for the rest of their lives. In this connection I should like to pay special tribute to two of these committeemen for exceptionally painstaking and effective criticism, Duncan Stewart and George Houston, and to include in this tribute an officer of the Institute, Alexander Konkle.

I must acknowledge also my indebtedness to a number of outside reviewers: C. N. Ostergren, American Telephone and Telegraph Company; Prof. Forest C. Dana, Iowa State College of Agriculture and Mechanic Arts; Prof. Eugene L. Grant, Stanford University; Prof. Walter Rautenstrauch,

Columbia University; Prof. C. E. Bullinger, Pennsylvania State College; Prof. Edmund D. Ayres, Ohio State University; and finally, Paul T. Norton, Jr., of The Case Crane and Kilbourne Jacobs Company, who merits special mention. An old friend of the Institute and a nationally known authority on equipment policy, Mr. Norton has been kind enough to give me at all stages of the investigation the benefit of his insight and experience. Although we have not agreed on all points, I have profited greatly from the interchange of views and owe him a debt of gratitude. Needless to say, neither he nor any other reviewer can be criticized for the final results, for which the Institute is solely responsible.

I come at last to my immediate collaborators. To Dr. Eric Schiff, who has been with the project throughout, and to Janet Peters, who shared in its earlier phases, I tender my appreciation for their able and untiring cooperation.

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Chapter I

INTRODUCTION

The transiency of human life has been a favorite theme of poets and philosophers since the dawn of history. Less poignant, but no less evident, is the transiency of man's handiwork. Of all the structures and artifacts of antiquity, only an infinitesimal remnant survives today—a few roads, bridges and aqueducts, a few monuments and temples, a few statues and pieces of pottery, some coins. Of the tangible products of the Middle Ages, not much remains save castles, cathedrals, and monasteries. Physical survivals from later eras are, of course, more numerous and varied, but save for the vintage of very recent periods they represent but a tithe of the "durable" goods originally produced. The life of most such goods falls far short of the three score years and ten the psalmist has allotted the human span. Indeed, in the United States at least, a typical year's output of durable commodities and structures has an average life expectancy less than half as long. The hand of time lies heavy on the works of man, whether ancient or modern.

This is a fact, obviously, of the most practical consequence. It confronts the owners of these nominally "durable" but nevertheless ephemeral goods with two problems. The first is to distinguish the quick from the dead; in other words, to tell whether goods not yet physically exhausted have outlived their economic usefulness, either generally or for the particular function they now perform. The second is to make financial provision against the wastage of durable assets over their service life. The one involves replacement, or reequipment, policy; the other, depreciation policy.

Since this is a book on replacement policy (the term

being construed more broadly than usual, as we shall see in a moment) it is concerned only indirectly and incidentally with accounting provisions for depreciation. While depreciation accounting is an interesting and important subject, it enters here only as it impinges on replacement policy, that is to say, only as it affects the character and timing of decisions to reequip.[1] That it does affect such decisions in many cases admits of no doubt, and we shall therefore have something to say about it in a moment. But first let us take a quick glance at the main subject of inquiry—replacement.

A PRELIMINARY LOOK AT REPLACEMENT

If all durable goods were like the "wonderful one-hoss shay"—requiring no maintenance, as good as new to the end, collapsing finally all at once in a heap of junk—and if they were not displaced before the end of their physical endurance by improved substitutes, the problem of when to replace them would be as simple as the problem of when to replace electric light bulbs. It so happens, however, that these conditions are rarely met. The majority of durable goods require during their service life a flow of maintenance expenditures, which as a rule rises irregularly with age and use. Most of them suffer a deterioration in the quality of their service as time goes on. Moreover, in a dynamic technology such as ours, they are subject to the competition of improved substitutes, so that the quality of their service may decline *relative to available alternatives* even when it does not deteriorate absolutely. Where these complicating factors are present, replacement does not await the ultimate physical collapse of the asset concerned—indeed in many cases this point is never reached if the parts are renewed piecemeal as they wear out—but is controlled instead by economic considerations.

There is a widespread tendency to think of replacement as the filling of a vacuum left by the physical collapse or deterioration of existing capital goods, and hence to under-

[1] The most recent of the Institute's studies in this field, cited in the Foreword, are *Depreciation Policy and the Postwar Price Level* and *Capital Goods Industries and Tax Reform*, both issued in 1947.

emphasize the dynamic effect of external technological and economic changes. Physical deterioration is still an important factor in limiting service life—varying widely in significance from case to case—but in the modern world external change must be given even greater weight. With the heightened tempo of scientific and technical progress, capital goods are increasingly pushed out of service, or *dis*placed, rather than merely *re*placed after they expire from physical decay. We have made this point in another context.

> Capital formation is not a polite game in which replacements meekly and decorously await, like dutiful heirs, the natural death of existing assets. It is a ruthless and cut-throat struggle in which new capital goods rob the function of the old. It is murder by degrees. We may add, parenthetically, that this displacement of function is frequently due to the competition of new goods quite different in character from the old. The function of the horse and buggy was appropriated by the automobile, which dispossessed likewise the electric interurban railway. The airplane displaces the ocean liner. Facilities for manufacturing nylon supersede the silkworm. Not only do the new capital goods differ from those displaced; it is obvious that they often have different owners. An investment by one company may in effect replace the facilities of a competitor by reducing or eliminating their function.[1]

Once we grasp the dynamic character of this process of mechanical displacement and transformation, the term "replacement" seems inadequate. It is too weak, too passive, too suggestive of the notion, to which we referred a moment ago, that new facilities merely fill a preexisting vacuum left by the demise of their predecessors. For this reason we have considered the possibility of avoiding the word entirely, employing instead such expressions as "displacement," "reequipment," or "remechanization." The term has the advantage of common usage, however, a consideration by no means negligible. Moreover, its suggestion of vacuum filling is not wholly in error, since most reequipment decisions turn in part on the physical deterioration of the incumbent

[1] *The Bogey of Economic Maturity*, p. 107, Machinery and Allied Products Institute, 1945.

asset, as well as on its obsolescence. We have decided, therefore, to continue to speak of replacement, with notice to the reader that we use the word as a synonym for remechanization in general, *hence with no implication of replacement in kind.* It applies equally whether the new facility is radically different from the incumbent or an exact replica thereof. It applies whether or not the function it performs is precisely the same.

Let this suffice for a first look at the concept of replacement, which will be further developed in the next chapter. Now that we know in general what the term means, we can consider and dispose of a subject introduced at the beginning but temporarily deferred, the relation of depreciation policy to replacement.

DEPRECIATION POLICY AND REPLACEMENT

Although authorities on equipment policy are by no means unanimous on the point, the prevailing view—with which we agree—is that replacement decisions should not be influenced by the book value, or unrecovered cost, of the asset considered for retirement.[1] Anyone who has sold industrial equipment is aware, however, that this rule is often honored in the breach. Not infrequently there is marked unwillingness to "take a loss" on the disposal of assets with substantial remaining book value, and their replacement is handicapped accordingly.

Right or wrong, rational or irrational, this prejudice exists in many places and must be reckoned with.[2] It means that a depreciation policy which yields a retarded write-off of capital assets is conducive to tardy replacement. This is true whether the inadequate write-off is due to improper methods of distributing depreciation over the service life or to excessive estimates of life expectancy. In either case we

[1] We shall argue the point later.

[2] A recent survey of machine tool users by *Iron Age* asked the question, "Would a change in depreciation policy under present income tax regulations induce you to buy more new machine tools if you were permitted to set up your own rates of depreciation higher than the present 6 or 7 per cent per year?" Of 512 respondents, 306 answered affirmatively, 206 negatively.

get higher book values than we should have and a consequent drag on modernization and improvement.

The impact of depreciation policy on replacement may take a slightly different form, however. Even when management entirely ignores remaining book value in its reequipment decisions (or thinks it does) it is not uncommonly influenced by a vague feeling that capital assets ought to be kept in commission over the service life assumed for depreciation purposes; hence this period becomes a kind of magnet, drawing replacement policy to it, not rigidly or invariably, to be sure, but with a subtle and persistent attraction.

It must be obvious that in so far as the period of service is influenced by the life span assumed for depreciation purposes, actual lives cease to be a test of the validity of the assumed lives and become instead merely their reflection. In practice, of course, this influence is never unilateral. If the real lives are modified by the assumed lives, the reverse is true also. What we have is a process of interaction yielding results in the nature of a compromise or composition. Certainly it is possible for the pull of depreciation life estimates to hold actual lives more or less consistently off the course they would follow in the absence of such estimates.

But this is not all. Replacement is affected by depreciation policy in still another way, through the influence of the latter on the supply of funds available for capital purposes, especially on the *timing* of the supply. Various methods of depreciation differ widely in the time distribution of the total charge over the service life. Methods that concentrate the write-off in the early years of life recover the bulk of the investment sooner (assuming the charge is earned) than methods that concentrate it in the later years or that spread it evenly; hence they provide an earlier receipt of funds for reinvestment. It follows that a growing economy or enterprise with its depreciable assets falling predominantly in the younger age groups will have consistently a higher aggregate depreciation charge under methods that concentrate in the earlier part of the life span. To the extent that capital expenditures

are influenced by the volume of depreciation accruals—and this influence is considerable—depreciation policy becomes an important factor affecting replacement.

We may summarize by saying that depreciation policy influences replacement policy directly, through a frequent disinclination to retire assets before the end of their estimated life, especially when they still have a substantial book value, and indirectly, through the impact on capital expenditures of differences in the volume of depreciation accruals. The extent of this influence in the United States it is of course impossible to measure, but it must be substantial. In the opinion of competent observers, this is true also in Great Britain, where depreciation policy is held to be "one of the factors—though not necessarily the most important one—which determine the rate at which British industry replaces its equipment."[1] The extraordinarily low rates of depreciation formerly taken in Britain, both for book and for tax purposes, have unquestionably contributed to the technological backwardness of industry in that country, of which we shall have more to say shortly.[2]

It may be argued that since replacement decisions *ought not* to be influenced by the depreciation status of the assets it is proposed to retire, the real remedy lies in securing an acceptance of this principle rather than in the improvement of depreciation policy itself. We agree that the principle should be emphasized and that its universal adoption would eliminate any drag on replacement arising from the depreciation status of existing assets, but as a practical matter no such universal acceptance is in sight. Even if it were, moreover, it would not do the whole job. We should still have to reckon

[1] *The Economist* (London), Jan. 2, 1943, p. 17.

[2] For examples of these rates, see the issue of *The Economist* just cited, p. 18. In comparing them with rates in this country, it must be remembered that they are computed by the declining-balance method. They are applied, in other words, to the written-down or depreciated value, not, as in the United States, to the original cost. It should be added that 1945 tax legislation improved the situation very markedly by allowing a special 20 per cent write-off in the year of acquisition (10 per cent for buildings and structures), and by increasing normal depreciation rates by one-quarter.

with the indirectly deterrent effect on replacement of too small a flow of depreciation accruals—the other, and perhaps even more important, aspect of the problem.

While both these considerations argue for the improvement of depreciation policy, there are other reasons for such improvement which have nothing to do with replacement and which are therefore beyond the scope of the present study. Depreciation accounting, as we said earlier, is a subject in itself. Having commented on its relation to replacement, we can now take leave of it for the remainder of the investigation, save only for one brief reference in another context. We return, therefore, to our main theme—replacement policy itself.

CONSEQUENCES OF BAD REPLACEMENT POLICY

As indicated in the Foreword to this study, the failure of industry to recognize the economic demise of its productive facilities and to accord them timely burial can have deplorable consequences for the country as a whole and may properly become a concern of national policy. No country can contemplate with equanimity the failure of its industry to keep abreast of technology. It deprives the state of power and security and robs the citizen of the advance in living standards to which he is properly entitled. When private enterprise develops a predilection for antiques as instruments of production it can expect sooner or later to come under the critical scrutiny of the state.

An outstanding example of such technological degeneration and of the state intervention to which it inevitably leads may be found in Great Britain. Here the government announced (1945) a far-reaching scheme to raise the productivity of private industry. For each of the covered industries, a "task force" or "working party" was appointed to make a technical survey of facilities, organization, and operating practices.[1] These survey committees were to recommend

[1] This scheme was sponsored by Sir Stafford Cripps, then President of the Board of Trade and more recently Minister of Economic Affairs.

programs of reorganization and plant modernization.[1] It was not clear just what sanctions and compulsions were contemplated for effectuating these programs—that delicate question being left to the future—but the implication was plain enough that the state would take whatever measures were necessary. In effect private business was put on notice that it would have to achieve efficiency on its own initiative—or else.[2]

At this writing, about a dozen of these working party reports have been published. They portray so strikingly the consequences of bad equipment policy that the Institute has reviewed them in a separate pamphlet, *Technological Stagnation in Great Britain*. Because of this review, we shall make no attempt to analyse the reports here but shall present instead some general comments on the situation from a different source:

> The public has in recent months waked up to the fact that the whole wealth-creating mechanism of the British community is badly in need of a drastic overhaul. Several of the basic industries—one is tempted to say most of them—are badly out-of-date in their productive equipment and methods. An hour of work in Great Britain produces less in material product, relatively to other countries, than it used to, and less than it will have to if the British people are to keep their place among those with high standards of living.
>
> British industrialists, with a few notable exceptions, have never been "re-equipment-minded." The general attitude towards plant replacement before the war was to scrap a machine only when it could no longer do the job for which it was originally designed. Only rarely was the question asked whether a new machine could do the job better and more economically than an existing one; or whether a new plant layout involving, say, two new machines instead of three installed, would do the job more economically still.

[1] A somewhat similar program was launched in France in the same year under the sponsorship of M. Jean Monnet, Chairman of the Commission for Industrial Modernization.

[2] Witness the statement of Emanuel Shinwell, Minister of Fuel and Power, that while it is planned to nationalize only 15 to 20 per cent of British industry "we shall demand of private enterprise that it do its utmost to achieve complete efficiency with the remainder." (Quoted in the *Wall Street Journal*, Jan. 24, 1946.)

For the moment, now that things have come to this pass, there is no satisfactory solution. Everybody has known this about coal for some years, and the only new discovery now is that there are many other industries in the same condition. Moreover, there is only one satisfactory long-term solution, and that is a rapid and drastic increase in the productive efficiency of the industries concerned. At whatever point an enquiry into British economic problems begins, it always ends up at the paramount need for productive efficiency. If the difficulties of this year and next serve to ram that lesson home, they may be the ill wind blowing good. They may even provide the country with a glimpse of the economic peril in which it stands.

The first essential is to find out how many of those sick industries there are—how many industries, that is to say, which are incapable of paying an attractive rate of wages, providing proper conditions of work, and at the same time producing on a competitive basis. The second essential is to set on foot a vigorous technical examination of these industries to determine how their productive efficiency can be raised to the necessary level.[1]

Since these words were penned four years ago, the "crisis of production" in Britain has remained acute. What is now evident is that there is no quick or easy remedy. Once the technology has fallen as far behind as it has in many British

[1] These are the views of *The Economist* (London), taken from the issues of Mar. 10, July 28, Aug. 4, and Oct. 6, 1945. They find general support in two recent books by Lewis C. Ord, *Secrets of Industry*, Emerson Books, Inc., New York, 1945, and *Politics and Poverty*, Funk & Wagnalls Company, New York, 1948, and are confirmed with respect particularly to industries in the Foot and Reid reports dealing with British coal mining, the Platt report on textile manufacturing, and, in general, by the working party reports. For a statistical comparison of prewar industrial productivity in Britain and the United States, see L. Rostas, *International Comparisons of Productivity in British and American Manufacturing Industry*, Macmillan & Co., Ltd., London, 1949.

We do not wish to imply that these commentators on the state of British industry stress the backwardness of its mechanical facilities as the *sole* cause of inefficiency. On the contrary, they recite a long list of factors, including faulty organization, poor marketing arrangements, restrictive labor practices, cartelization and restraints on competition, inadequate scientific research, repressive taxation, traditionalism, insufficient managerial skill, and so on. Backward equipment policy, though the most important single contributor to low productivity, is thus by no means the only factor in the picture. See the remarkable series of articles on *A Policy for Wealth*, appearing in *The Economist* (London) during August, September, and October, 1944, and later reprinted in pamphlet form.

industries, it is a long and arduous task to catch up—much harder, indeed, than to keep up in the first place. For the process of degeneration tends to feed on itself, a proposition illustrated by one of the working party reports:

> The cessation since 1923 of purchases of new machinery is disturbing, for a vicious circle is created. If new machines are not being bought, then little or no research will be undertaken by machine builders into possible technical improvements. And without these improvements the familiar argument that the old machines are as good as the new must carry with it a substantial element of truth.[1]

Certainly if British industry does not forthwith modernize itself it will not be for lack of exhortation. The working parties have done some excellent preaching, so much so, indeed, that we cannot refrain from one quotation:

> It is necessary if the trade is to enjoy robust health, that firms should be ready and keen to rebuild, renovate and re-equip at each stage of progress as soon as it becomes commercially practicable to do so. Unless the will is strong in this direction there develops an increasing tendency to be satisfied with short-term profits and to hold on to old buildings and old equipment to the bitter end, in the meantime building up no adequate resources for replacement, when allowance is made for present-day building costs. It is possible in this way for an almost hopeless position to arise in the industry without there being any general recognition of what is happening. There is more than a danger, in our view, that this has happened, or is happening today, in a large section of the trade. We cannot press too strongly upon the industry that it should take steps without delay to take stock of its present position, collect and face courageously the facts and figures, which could not but show, in our opinion, that a change of policy is overdue, and devote itself whole-heartedly to the fulfilment of a re-building and re-equipment plan such as would put the whole industry on a thoroughly modern basis.[2]

With this admirable preachment, we take leave of Britain and direct our attention to the American scene.

[1] *Report of Working Party on the Lace Industry*, p. 40.
[2] *Report of Working Party on Jewelry and Silverware*, p. 29.

AMERICAN PRACTICE

We are accustomed to consider American industry a model of vigor and enterprise in adopting advances in technology, especially in the improvement of its mechanical facilities. We have the legend of the industrial executive, avid for the very latest productive equipment, discarding unhesitatingly and without compunction the still serviceable tools of yesterday the moment something better comes along. Certainly this idealized picture is not without its counterpart in real life, but it must be acknowledged that such zeal and audacity are far from universal. Our practice may compare favorably, by and large, with practice in other countries, but it nevertheless falls far short of what it should be. We venture to assert that a careful survey of the productive facilities of American industry would disclose a sizable fraction in use beyond the proper economic life for the function or service performed. This country too has its quota of mechanical zombies.

One reason for this condition—though by no means the only one—is a frequent lack of understanding by business management of the principles properly governing the economic life of a productive facility. There are available, of course, a multitude of "replacement formulas," but unfortunately most of them are too complex for the average executive. Even more unfortunately, they yield widely different results when applied to the same set of facts; hence it is often more difficult to decide which formula is correct than to apply the one selected. For these reasons it is not surprising that elaborate mathematical procedures for timing replacement have only a limited currency in American industry. They yield in practice to a simpler application of "business judgment," aided frequently, in lieu of a more scientific formula, by some simple rule-of-thumb test that happens to be favored by the management concerned.

Certainly there can be nothing wrong with the application of business judgment to this problem; indeed it is indispensable. No magic formula exists or is in prospect by which

decisions in this field can be delegated to a clerk with a slide rule. As we have already remarked, replacement is rarely the installation of a new unit of plant or equipment identical with the one removed—if it were only that, the clerk might suffice—but is more likely to be the substitution of an improved and often radically different unit or combination of units. The more dynamic the technology concerned and the more numerous and varied the alternatives, the less adequately will any mathematical formula fit the case, and the greater must be the reliance on personal judgment.

Since the use of full-fledged replacement formulas is comparatively rare in American practice, but the use of conventional rule-of-thumb tests of replaceability very common, it is important to examine these shorthand aids to managerial judgment. Do they make sense? Can they be justified on theoretical grounds? Do they command general acceptance? That the most popular rules of thumb are not rationally justifiable, we shall argue later. The point to emphasize here is the absence of agreement on the rules themselves. There is, in fact, an amazing diversity in their application.

We can illustrate by the results of a recent survey of machine tool users, to whom the following question was addressed: "If you would replace existing machine tools before they are actually worn out physically, how much saving in per cent of cost of new machine tools would have to be shown to induce their purchase?" The replies were distributed as follows:[1]

Required Annual Saving as Per Cent of Cost of New Machines	*Per Cent of Replies*
10	9
15	5
20	24
25	22
33	23
50	13
100	4
	100

[1] Survey by *Iron Age*, reported in issue of Sept. 11, 1947. It covered 560 companies.

Here is a short-cut device involving only a simple ratio between two magnitudes—the annual saving and the cost of the new machine—yet in application this ratio ranges from 10 to 100 per cent.[1]

Many American managements make replacement decisions without benefit even of a rule of thumb. The answer is "hunched," sometimes after much weighing of the pros and cons, sometimes with little more analysis than one might devote to the replacement of a pair of shoes. Whether the decisions issuing in this fashion from the managerial bones are better than those obtained by the application of a customary rule depends, of course, on the quality of the intuition—and the nature of the rule—in each case. No general answer is possible. The point is that by either procedure management is really shooting in the dark.

That some of this shooting results in premature replacements is highly probable. It is our firm belief, however (to be supported later) that in the main it errs in the other direction. We have still a long way to go before we have a productive establishment as modern and efficient as a sound analysis of comparative advantage can warrant. Hence the justification of the present study.

LIMITATION OF THE STUDY TO PRODUCERS' GOODS

Before we bring these introductory observations to an end, it may be well to point out a limitation of the coverage of the study, and the reasons therefor. It is limited to producers' goods only.

We said at the outset that durable goods are usually replaced for economic reasons. In the case of consumers' durables, however, such as houses, passenger automobiles, vacuum cleaners, furniture, or fur coats, the term "economic reasons" is obviously too restrictive. Replacement decisions reflect a varying admixture of motives, a compound of economy, emulation, prestige, artistic satisfaction, conformity

[1] The diversity may be even greater than this suggests, since there is no uniformity whatever in the reckoning of the annual saving.

to convention. Where these noneconomic considerations enter, only the comparative *cost* of the services of existing goods and of possible replacements is an objective question; the comparative *valuation* placed upon such services is decidedly personal and subjective. It is possible to compute for milady the annual cost of owning a new fur coat, but we cannot compute for her the annual value of its use. That is for her to judge. Because of the essentially subjective character of these valuations, replacement decisions for consumers' durable goods are rarely made with a sharp pencil and a set of figures. They get made, somehow, by the inscrutable mental calculus implicit in all decisions, without benefit of formulas or equations.

The case is different with durable goods owned and operated for profit. Here the question of when to replace involves a comparison of money flows on both sides of the equation—costs on the one hand, income or earnings on the other. We are dealing on both sides with objective, measurable realities, usually involving an element of estimate and prediction, to be sure, but—unlike consumers' valuations—subject to expert judgment and technical appraisal. We may be able to show Mr. Jones that it would be cheaper to trade in his passenger car for a new one every four years instead of every year, but if he replies that it is worth the extra cost to drive a new car all the time, that is the end of the argument. "Concerning tastes there is no disputing." If, on the other hand, we can show Mr. Brown who operates a trucking company that he will make more profit by using his trucks four years instead of one, he will have to prove that we are wrong or stand convicted of willful stupidity. When the test is dollars and cents, we can talk a common language.

Because of these considerations, we shall confine our analysis of replacement policy to durable goods operated for profit—the facilities of production—often loosely described as "producers'" or "capital" goods. This is not only the principal area in which fruitful discussion of the problem is possible; it is also the area in which policy may become a

matter of national concern. The replacement problem of milady with the fur coat we leave for intuitive solution.

CONCLUSION

So much by way of general introduction. It is unnecessary, in view of earlier comments in the Foreword, to speak further of the character, purpose, and justification of this study. We should like to reiterate, however, that the book is not a treatise on the making of engineering economy studies, of which there are several already available. It is not a manual of procedure and practice. Rather, it is an attempt to explore the basic theory of the subject. It attempts further to develop some simple tests of replaceability more scientifically acceptable than conventional rules of thumb and less elaborate than existing mathematical formulas.

It requires some temerity to invade, as this work does, a well-tilled field of inquiry in which the literature is already voluminous. We do so, not to repeat what others have said, but rather in the belief that the previous tillage of this field has not gone deep enough. If we are right that a further penetration of the theoretical subsoil is needed, we have full justification for the effort, if not for the result.

Chapter II

THE NATURE OF REPLACEMENT

We emphasized in the preceding chapter the dynamic character of the replacement process. Capital goods live out their mortal span in an atmosphere of combat, a struggle for life as bitter, as intolerant of weakness, as the tooth and claw of biological competition. In principle, this mechanical warfare surpasses in depravity the carnage of the jungle: the beasts respect their own kind, but machines destroy their own species and others indiscriminately. In principle, also, mechanical combat is the more dynamic. The denizens of the jungle enjoy a limited security by reason of the continuity and stability of the species that prey upon them. However perilous the environment, it has for this reason a measure of predictability. Machines, on the contrary, must defend themselves in a world where new species spring up overnight, where the landscape is never twice the same, where the fitful winds of change are never stilled.

There is another contrast between biological and mechanical competition. In the former, death strikes suddenly, by violence; in the latter, it comes usually by degrees, through a process that may be described as functional degradation. It is a kind of progressive larceny, by which the ever-changing but ever-present competitors of an existing machine rob it of its function, forcing it bit by bit into lower grade and less valuable types of service until there remains at last nothing it can do to justify further existence. A capital good that can no longer hold some useful function against competition is a mechanical cadaver, whether buried or not. By the same token, an asset that has been forced into low-grade service through the expropriation of its original function is dead in

part. In the bloodless warfare of machines, life is taken, as a rule, by stages.

FUNCTIONAL DEGRADATION

Consider, for a moment, the case of the "wonderful one-hoss shay." This remarkable vehicle ran for a hundred years, as good as new, until it suddenly collapsed, catastrophically, in a pile of junk. Assuming—since the narrative is silent on the point—that the quantity as well as the quality of its services was unimpaired to the end, it is clear that the shay was not replaced functionally until after its collapse. Its demise left a functional vacuum which the successor vehicle filled.

Consider now, by contrast, the life history of a freight locomotive of the vintage, say, of 1890. It began in heavy main-line service. After a few years, the improvement in the new locomotives available and the development of the art of railroading made the unit obsolete for that service, which was taken over by more modern power. It was thereupon relegated to branch-line duty where the trains were shorter, the speeds lower, and the annual mileage greatly reduced. For some years it served in that capacity, but better power was continually being displaced from main-line duty and "kicked downstairs" onto the branch lines, and eventually our locomotive was forced out at the bottom, to become a switcher in one of the tanktown yards along the line. But the march of progress was relentless, and in the end, thanks to the combination of obsolescence and physical deterioration, it wound up on the inactive list. For some years more it lay around, idle most of the time, but pressed into service during seasonal traffic peaks and special emergencies. Finally, at long last, the bell tolled and it passed off the scene to the scrap heap.

While the passing of the one-hoss shay left a functional vacuum to be filled by its successor, the retirement of the locomotive was merely a belated recognition of the fact that it was already dead from a functional standpoint. Its departure created not so much as a ripple in the operation of

the railroad. Unlike the shay, which maintained the full integrity of its original service to the end, and which was functionally replaced, therefore, *after* retirement, the locomotive was replaced *while it was still in service*. Its final retirement was merely an aftermath of replacement.

Now most capital goods fall somewhere between these two extremes. They suffer a partial displacement of function during their life, with the remainder displaced at retirement. Typically they undergo during their active careers an irregular down grading of function that reflects this partial displacement. New houses are built for the most part in new neighborhoods and for occupancy by people of above-average income, but as they age, stylistic and technical obsolescence and neighborhood deterioration commonly shake them down into lower and lower classes of occupancy. Automobiles ordinarily pass through two or more hands on their way to the scrap heap, not only rendering a progressively deteriorating quality of service but running fewer and fewer miles per year. Production equipment is frequently resold in used condition, occasionally several times, going generally into lower grade uses requiring less precision and reliability and less continuous service. Even when it is held until final retirement by the first buyer, it tends to gravitate with increasing age into low-precision operations and discontinuous service, winding up frequently in a merely protective, or stand-by, capacity.

The debasement of function over the life of a capital good may be either quantitative or qualitative. That is to say, there may be a decrease in the *amount* of service rendered as the unit ages or a deterioration in the *quality* of the service, or both. A combination of the two forms of degradation is characteristic of most kinds of movable productive equipment, whereas for buildings and other structures qualitative degeneration is predominant.

QUANTITATIVE DEGRADATION

For obvious reasons, the measurement of decline in the amount of service rendered—in terms of hours worked or

miles run per year, for example—is easier than the measurement of decline in quality, though the statistical material available for either purpose is exceedingly meager. By way of illustrating the quantitative aspect of service degradation, we have shown in Chart 1, the typical decline of service intensity with age for eight items or classes of productive equipment: locomotives, agricultural implements, tractors, buses, passenger cars, trucks, truck tractors, and trailers.

While these eight types of equipment are not so broadly representative as one could wish, overweighted as they are with motor vehicles, they present a consistent pattern of service intensity declining with age that is undoubtedly characteristic of standard productive equipment generally. Where a machine can be shifted as it ages to jobs of lower continuity and intensity, either within the same ownership or by transfer in the secondhand market, quantitative degradation of function is highly probable.

Now it must be obvious that this decline of service intensity with age does not just happen; it is in fact a reflection or manifestation of the growing *qualitative* superiority of the service offered by available substitutes or alternatives for the existing asset. This superiority may reflect an actual deterioration in the service of the aging facility, or merely an improvement in the currently available alternatives without such deterioration, but in any event a gap opens up, servicewise, between the asset and its competition, making it vulnerable to displacement. Naturally, its vulnerability is greatest, other things equal, in high-intensity assignments in which the greater capital charges incident to new facilities can be spread over a larger production. Such assignments are usually the first to go. Where tasks of lower continuity are available, the aging asset normally sinks into intermittent employment, in which it can defend itself against the wolves of competition.

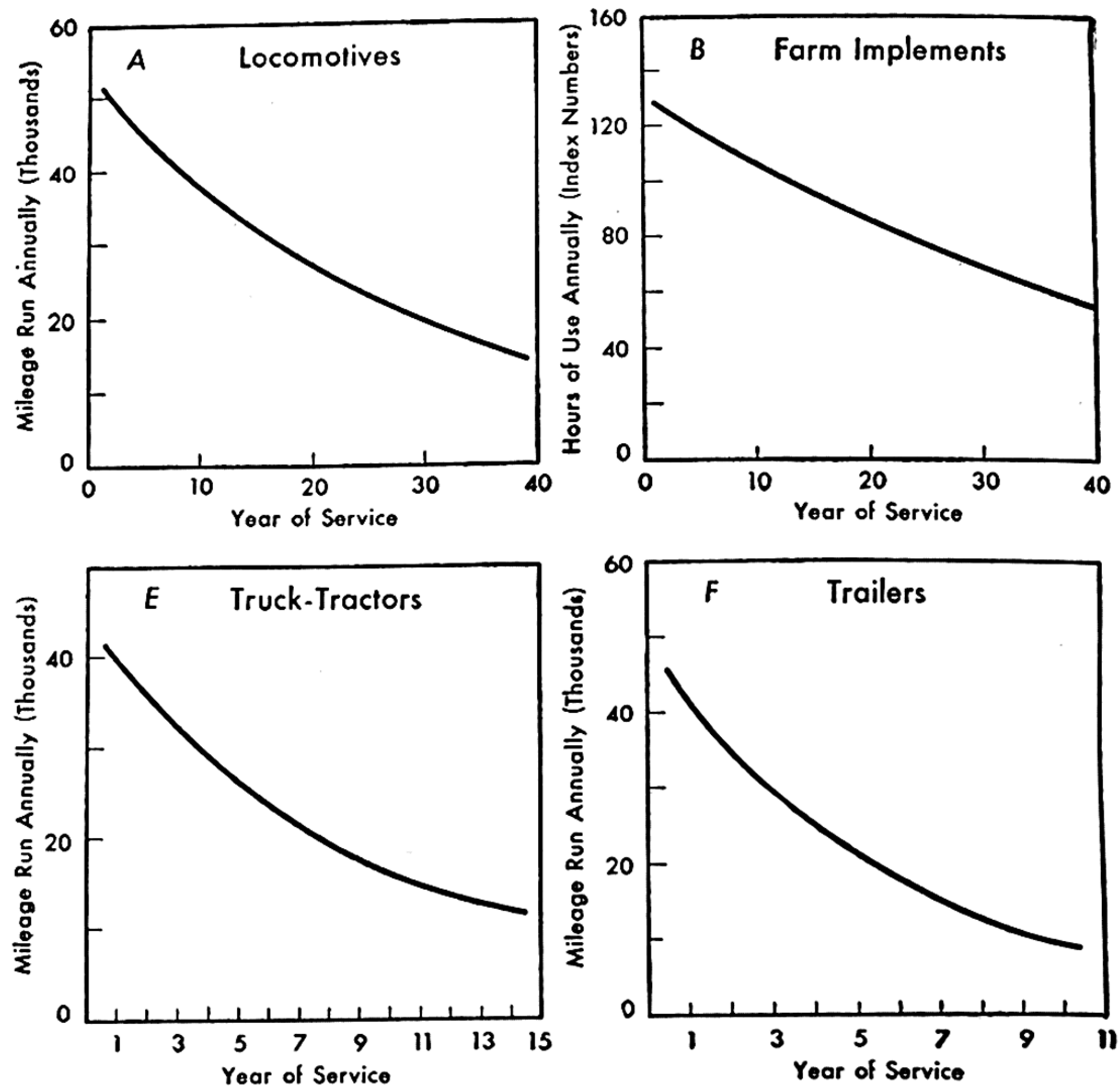
QUALITATIVE DEGRADATION

The retreat into jobs of lower service intensity is not the only means bv which aging facilities maintain their hold on

life, however; they prolong their existence also by finding work of lower quality, in which the service superiority of new and better substitutes is less important. Thus a machine tool that has lost some of its original precision but is otherwise

CHART 1

RELATION BETWEEN AGE AND INTENSITY OF USE



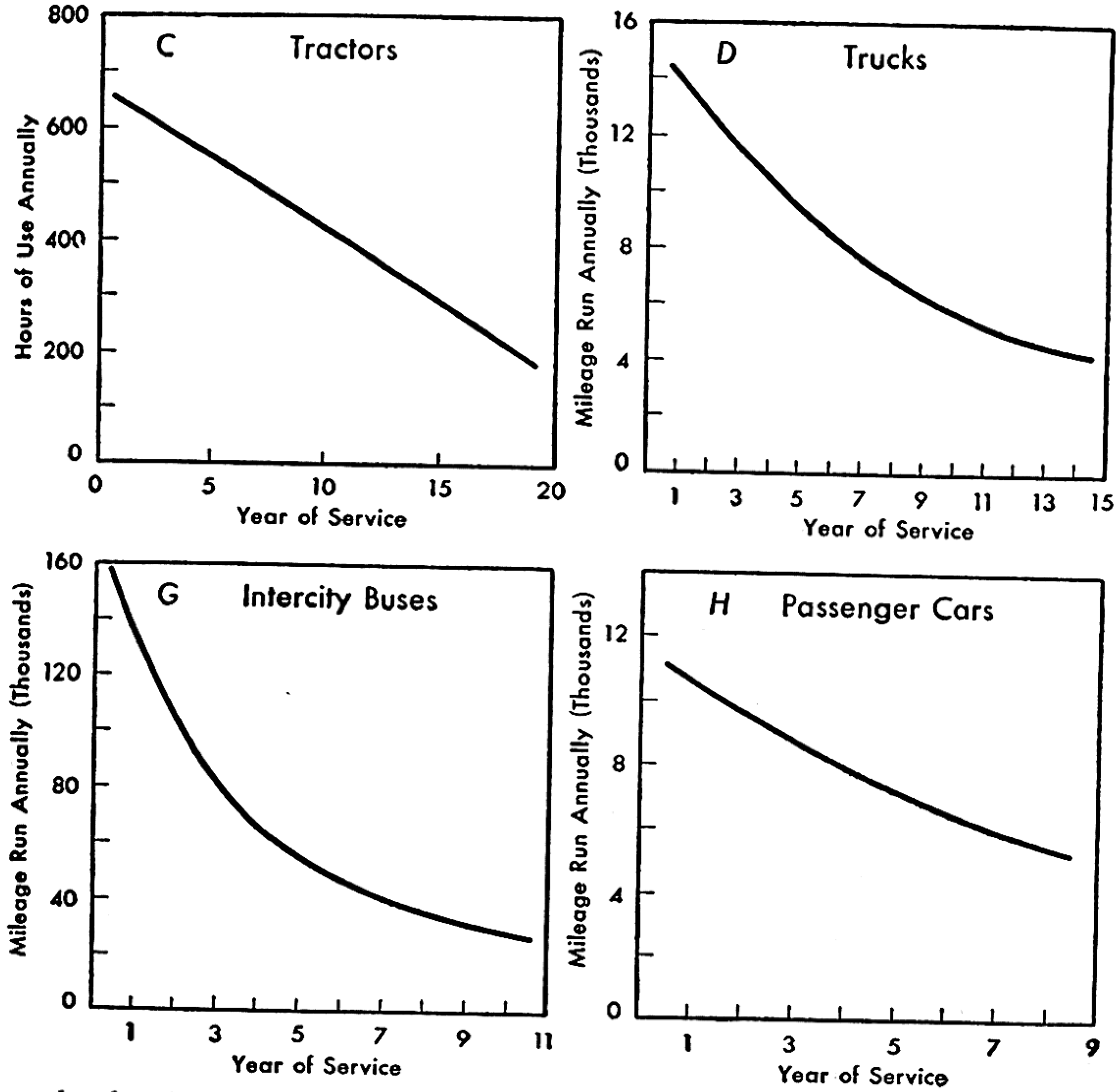
[a] For sources and methods, see page 243. The curves are smoothed trend lines drawn through the actual data. It should be pointed out that these measures of declining use intensity compare units now old with other similar units now new, not old units *with their own past.* Mileage run or hours worked per year during the

serviceable may gravitate toward assignments for which the requirements are less exacting. Or a bus that has yielded the cream of its service in main-line, long-distance runs may be relegated to a short feeder route. In many cases this descent

Acc. No. 12971.

into service of lower quality is accompanied by reduced intensity of use, but in others it is not. Qualitative and quantitative downgrading may be conjoined or either may proceed without the other.

CHART 1 (*Continued*)
FOR EIGHT CLASSES OF PRODUCTIVE EQUIPMENT[a]



youth of units now old undoubtedly differed considerably from the current figures for presently young units. The results must be taken therefore as only roughly indicative of the course of use over the lives of identical units.

In the case of housing, for instance, there is rarely any marked decline of service intensity, as measured by occupancy ratios, until near the very end of life, but there is normally a deterioration of quality. This can be roughly gauged by the decline of rental value with increasing age of structure. The

following table shows median rental values for 1940 for all dwelling units in the metropolitan areas of the United States, by age groups.[1] The deterioration of the quality of service with advancing age of structure is apparent, dwelling units over 50 years old having a median rental value of about half that of new units.

Age of Structure, Years	*Median Monthly Rental Value per Dwelling Unit*
Under 10	$42.09
10 to 20	37.34
20 to 30	30.05
30 to 40	26.06
40 to 50	23.42
Over 50	21.06

This decline in the rentals is due not simply to retrogression from the original condition of the structures and neighborhoods; it registers also dynamic changes in the pattern of demand for housing—affecting style, materials, equipment, layout, location, and surroundings—changes which lower the relative desirability of the older dwellings in comparison with the new.

Capital goods are "kicked downstairs" in the scale of service not simply because new facilities are developed that can perform better or cheaper the *same* service rendered by existing units. The service itself may be outmoded by the progress of the arts or by changes in demand. The forced conversion of livery stables to other uses did not reflect the pressure of better facilities for accommodating horses; it denoted the supersession of the horse by motor vehicles. Qualitative downgrading results not merely from a worsening of the service as compared with what it was when the same capital asset was new, but also a worsening relative to the service—competitive, but often quite different—obtainable from a more modern substitute.

Thus the war of machines is not merely, or even primarily, a struggle for the privilege of performing a preexisting function

[1] Computed from the 1940 census report, *Housing*, Vol. III, Part 1, p. 24.

or service, though occasionally this is the only thing at issue; it is a more complex affair in which the improvement of the service itself is often the most effective and lethal offensive weapon. The ability of a challenger to perform a superior function can dislodge an existing asset quite as well as its ability to perform the same function in a superior manner. Both factors combine to intensify the ceaseless aggression of the new against the old, the bloodless brigandage by which existing assets are robbed of their functions and shouldered at last into outer darkness.

WHAT IS REPLACEMENT?

We have discussed the phenomenon of functional degradation at some length because it must be understood if we are to grasp the essential nature of the replacement process, to which we now turn.

Let us revert to the hypothetical freight locomotive mentioned earlier in this discussion, downgraded during its life from main-line to branch-line duty, thence to a switching yard, and finally to occasional or stand-by service in emergencies only. When was this locomotive replaced? As we said, its actual retirement was merely a belated recognition of the fact that it was already dead from a functional standpoint. Its departure left no functional vacuum to be filled. Replacement had occurred long since, piecemeal and by degrees, when and as its function was appropriated by better power. We have here the key to the understanding of replacement in a dynamic society. *It is the displacement of capital goods from their function or service.* It is functional robbery.

This is a broader conception of replacement than prevails generally.[1] According to one common view, each capital good is replaced but once, at the time of its final abandonment or scrappage. By another view it is replaced whenever it is retired from ownership, regardless of whether it is scrapped

[1] In preferring this definition we by no means imply that all others are "wrong." Fundamentally, definitions are not right or wrong; the test is rather their serviceability for the purpose in hand.

or put into use by the purchaser. In our opinion both views fail to get to the heart of the matter. The final abandonment of an asset may be simply an aftermath of a process of functional erosion extending over many years, hence an event in itself of no particular consequence. As for identifying replacement with transfers of ownership, this is equally unsatisfactory. Whether functionally displaced assets find an alternative service in the same organization or are transferred in the secondhand market to some other user is irrelevant. Both of these popular concepts turn on what happens to an asset *after* replacement but fail to define replacement itself—the appropriation of the asset's function by a competitor.

In our view a capital good is replaced as often as its current job or work assignment is taken over by a successor. If, like the "wonderful one-hoss shay," the asset defends itself against functional displacement to the very end of its career—and there are some types of capital goods, like railroad crossties, for example, of which this is characteristic—replacement occurs only once. If, on the other hand, the asset undergoes in service a course of functional degradation, it may be replaced any number of times, depending on how we define separate jobs or work assignments. The principle is the same in either case. Certainly it is immaterial in principle whether it is the asset's last function or its first that is taken away from it, or whether upon displacement it finds an alternative service or goes at once to the bone yard. It is immaterial also whether its next assignment, if any, is in the same ownership.[1]

"PRIMARY" AND "SECONDARY" REPLACEMENT

If replacement is the functional dislodgment of an existing facility, it may occur, obviously, without the acquisition of any

[1] When the number of units of equipment in the same ownership is large, as in the case of railroad locomotives, functional downgrading may be accomplished wholly or in part within the organization, but when there is but one unit per owner, as with farm implements or passenger automobiles for the most part, it is accomplished by transfers in the secondhand market. The units move from one owner to another in the descent to lower grades of service.

new asset by the same enterprise. The function of the displaced facility may be either taken over or superseded by the service of other equipment in the same ownership. In many types of operation such inside, or "secondary," replacement is far more frequent than replacement by new acquisitions ("primary" replacement); it occurs in fact whenever functions or job assignments are reshuffled among existing units. It follows that replacement policy is much broader than acquisition policy. Its task is not simply the procurement of new facilities which can economically take over the functions of existing equipment; it is the assignment of the existing equipment itself to secure the highest service at the lowest cost. Replacement policy should insure that all facilities in service are able to defend their functions against economical displacement by any challenger, whether outside or inside the same ownership.

It must be obvious that the considerations governing primary replacement, with a new commitment of capital, are quite different from those governing the functional reassignment, or reshuffling, of assets already owned. For this reason, while it is proper to include both forms of replacement in any fundamental definition, it is proper also to distinguish them for the purpose of discussion. This we shall do. Having included the secondary form to complete the conceptual picture, we shall henceforth have nothing further to say of it. We are interested here in primary replacement only—that is to say, in the functional dislodgment of existing facilities *by others newly acquired for the purpose*. When we use the word "replacement" hereafter, it will be with this meaning.

REPLACEMENT THROUGH COMPETITION AMONG ENTERPRISES

We indicated in the preceding chapter, but without commenting on the point, that facilities in one enterprise may have their function appropriated, or displaced, through the competition of facilities in another ownership. Let us take a brief look at this form of replacement.

When one enterprise diverts business from another, thus appropriating in whole or in part the function of its productive

equipment, this may or may not be due to superiority in the equipment of the successful competitor. Success in competition turns on a whole range of factors, of which equipment policy is only one, their relative importance varying widely from one type of industry and operation to another. In many lines a company can move up because it has better research, better product design, better sales organization, better advertising, better financing, better personnel, better trade connections—or what have you—even though its equipment is inferior. In other lines facilities policy is a strategic, if not a dominant, area of competition. A firm of lawyers will hardly sink or swim because of the condition of its typewriters, desks, and filing cases, but a steel company may be ruined by failure to keep its equipment competitive.

Since equipment policy is usually but one of many instruments of aggression and defense in the struggle for business and since the functional displacement of facilities through enterprise competition necessarily reflects the combined effect of all elements of policy, defense against such displacement calls, obviously, for efficiency on every front—research, design, development, purchasing, production, selling, financing, labor relations, public relations, and so on. However important it may be, equipment policy alone cannot protect the facilities of an enterprise against the loss of their functions to other producers.

It is not the task of equipment policy to defend the competitive position of a business single-handed, like Horatius at the bridge, but rather to make its proper contribution to a combined operation. To put it otherwise, the function of replacement by the individual enterprise is to minimize the risk of replacement through competition. It should guarantee that competitors gain no advantage from superior equipment policy. That is all it can do. If they win by other weapons, the result may be the same—appropriation of the function of the loser's facilities—but the blame will have to fall on other sectors of management. The equipment engineer can sleep with a clear conscience.

While it is essential to include replacement through competition in any broad description of the process of capital formation and retirement, we are concerned in this study with replacement *as a managerial problem of the individual enterprise*, not as a broad economic phenomenon.[1] For this reason we shall have no occasion to discuss further the process of replacement through competition among enterprises, important as that is from the standpoint of general economic analysis. From the standpoint of management, competition is simply an environmental factor conditioning replacement decisions along with others. It is the background of policy. We are interested in the policy itself.

THE RELATIVITY OF OBSOLESCENCE

There is one corollary of our definition of replacement that is worth a passing comment, namely, the relativity of obsolescence. Since replacement is the functional dislodgment of an existing asset, it follows that the obsolescence of that asset must be defined *in terms of its relation to its job*, not in terms of age or decrepitude as such. It is obsolete for the job when it is economically replaceable. Obviously, it need not be obsolete for all other jobs; indeed there may be many in which it can successfully defend its tenure. Obsolescence is thus a matter of relativity, not an attribute of the asset itself.

This is a point worth emphasizing, in view of a widespread tendency to associate obsolescence simply with age. We hear, for example, of a manufacturer who makes a practice of retiring equipment when it is 10 years old, and another who makes economy studies of equipment reaching that age in order to compel it to justify any further retention. Certainly it is better to scrutinize regularly items over 10 years of age than to have no systematic checkup at all, but we cannot accept the implication of this policy that obsolescence is confined to the upper age brackets. It can occur at any age. Indeed young assets in high-grade service are often more

[1] For a broader discussion, see *The Bogey of Economic Maturity*, Chaps. VII and VIII.

vulnerable to displacement than old assets in low-grade service. There is another point to be noted: The loss from the miscasting of equipment is likely to be greater, the higher the intensity and quality of the service involved. Hence no productive facility should be exempt from challenge merely because of its youth.

We have said enough on the general concept of replacement, on the qualifications and limitations of this concept for the purpose of our study, and on its implications. All this is of course merely preliminary to the main task, the development of sound replacement policy. Here the going gets difficult. There is no bell that rings when the economic life of an asset expires, nor are there any physical stigmata to distinguish the dead from the living. How can we tell whether a facility has a valid title to its present function? This question will lead us over a long and difficult road, on which we set out in the next chapter.

Chapter III

FIRST APPROACH TO REPLACEMENT ANALYSIS

A capital good, such as an office building or a tractor, is essentially a store or reservoir of future services. The office building represents perhaps 50 years of usage wrapped up in one package, the tractor, say, 15 years. It is not too fanciful, therefore, to liken the market for capital goods to a futures market for services, with the trading predominantly in large lots and with progressive deliveries over long periods of time.

There is also a spot market for the services of capital goods, with trading, as a rule, for near-term delivery only. We refer, of course, to the rental market. Here services are bought and sold, usually for brief periods, without transferring the ownership of the goods themselves. The futures, or sale, market deals in the services of an asset on an all-or-nothing basis; the spot market can dole them out with an eyedropper.

When the users of productive equipment purchase its services in the spot market, their replacement problems are relatively simple. Suppose, for example, we have an operator who rents his equipment by the month from competitive suppliers. In this case the question of how to equip for a given job or process offers no theoretical difficulty whatever. Since capital cost becomes under this arrangement a current cost comparable to wages and salaries, there is no difference in principle between equipping an operation and staffing it with workers, or between replacing the equipment and replacing the workers. It is simply the practical problem of getting the most for the money, now.

Where the facilities are owned by the operator, on the other hand, the problems of mechanical and human replace-

ment take on a quite different character. While workers carry price tags on their current services—so much per hour or per month—machines have no similar identification. Their capital cost is paid in a lump sum in advance of use, and the amount properly chargeable to any current or future period is problematical. Moreover, since the facilities are subject to deterioration and obsolescence over their service lives, their present performance cannot be projected into the future. It is necessary to adjust for these degenerative factors, and this adjustment is also problematical. It is not surprising, therefore, that the replacement of owned assets has engendered a controversial confusion recalling the Tower of Babel, a confusion the owners of slaves were spared, incidentally, when the Emancipation Proclamation abolished the futures market in human services. For the slaveholder confronted the same problem that still bedevils the owner of machines.

I. Replacement of Rented Equipment

It may surprise the reader to find the exposition of replacement theory beginning with rented equipment. We start with this case, not because of its importance in fact—the leasing of equipment is widely prevalent only in a few lines—but rather because of its simplicity.[1] It provides for this reason a convenient point of attack on the whole problem,

[1] There are various reasons for this relatively limited rental market. In some cases the facilities are so specialized to the needs of the user, with so little value for other purposes, that no one could safely supply them on a rental basis except on a lease so long the transaction would be tantamount to sale. Consider, for example, a production tool specially designed to machine one particular piece. In other cases where the care and maintenance of the facilities are crucially important and where it is impracticable for the lessor to service them himself, the difficulty of enforcing proper standards on the lessee is sufficient to discourage renting. This is true of a great deal of intricate machinery. In still other cases the cost of dismantling, transporting, and installing the facilities on the premises of another lessee is so high as to prohibit their availability on a rental basis except on very long leases. Take as a case in point a heavy forging hammer requiring a specially built foundation. There are other reasons why the leasing of productive equipment—as distinguished from real estate and improvements—is comparatively rare. For a good discussion of this subject, see "The Lease as a Marketing Tool," *Harvard Business Review*, 1944, p. 415.

permitting us to ease into the analysis gradually, without confronting all its complexities at once, and to nail down in the process certain points and principles that will be applicable later when we come to ownership replacement, the main subject of the inquiry.

Suppose a certain type of productive equipment is leased by the year in a competitive market.[1] How does the replacement problem appear to an operator now renting machine *X* for a certain job or function, in view of the availability of alternatives *A*, *B*, and *C*? Obviously, the problem is to get the best service for the lowest combination of rental and operating cost. If the alternative machines render exactly the same service as the one now in use, it is simply a question of comparing differences in the rental charge with differences in the cost of operation; but if, as usually happens, there are disparities in performance or service value, an allowance must be added for this factor. Suppose the line-up of possibilities is as follows:

	Estimates for next year			
	Present machine	Alternatives		
	X	*A*	*B*	*C*
Operating cost	$10,000	$ 7,000	$ 4,000	$ 5,000
Service superiority over *X* (subtract)	0	0	500	1,000
Rent	3,000	5,000	7,000	7,000
Total	$13,000	$12,000	$10,500	$11,000

Assuming our operator is right in weighing the replaceability of *X* separately—an assumption discussed in a moment—he cannot be in doubt of the result: machine *B* will save

[1] We prescribe short leases for this illustration because the replacement of long leases takes on many of the characteristics of ownership replacement, which we shall discuss later.

$2,000 in the following year in out-of-pocket cost (operation and rent combined) but since its service is worth $500 more than the service of *X*, the total advantage is $2,500. This exceeds by $500 the advantage offered by the other possibilities. The case decides itself; *X* must go. We have here no mysteries, no replacement formulas, no rules of thumb. We do have, of course, an expression of business judgment in the estimates of operating cost and service superiority for the various machines, but these involve no questions of theory or principle; they are simply questions of fact, the routine, everyday stuff of managerial decision.

We have assumed, as stated, that our operator is right in weighing the replaceability of machine *X* separately. But he may not be. Tooling for a complex process of production is governed by a kind of non-Euclidian mathematics: the whole may not equal the sum of its parts. It is possible to have the best available machine for each separate job or function as presently set up but nevertheless to have the entire layout replaceable as a whole. Suppose our operator, aware of this hazard, wishes to test the relative merits, not of various alternatives for a single machine, but rather of alternatives for a whole group or series of machines. Say he is testing the replaceability of an entire layout comprising 10 units, the alternatives being three different combinations numbering 5, 8, and 10 machines. These groups can be treated exactly like the single machines in the table above.

Under our hypothetical rental system the test of replaceability for a block of facilities is thus precisely the same as the test for a single unit. It is true that in these group comparisons there is more figuring, more estimating, more judgment, but these are the things management is paid for. The applicable principles are the same. Our suppositious lessee can test the advantage of retooling a single operation, a limited sequence of operations, a complete process, or an entire plant, as he chooses, without becoming involved at any stage in the mystery and mumbo jumbo so characteristic of replacement analysis under conditions of user ownership.

He has to make judgments and gamble on them, but he does not have to be a theorist or a mathematician.

THE PRINCIPLE OF TOP-DOWN MEASUREMENT

It is the great advantage of replacement in a short-lease rental market that once the various possibilities have been canvassed all cards lie on the table face up. As we have seen, when the lessee has made his estimates of the operating cost of various alternatives for the coming year and has adjusted them for differences, if any, in the quality of the service, he need only add the rent to identify instantly and unequivocally the unit or group of units yielding the lowest total cost for the service rendered. Because the answer lies face up, however, we have here an excellent opportunity to test one of the replacement procedures commonly employed under conditions of user ownership. We refer to the practice of computing what the user can afford to pay for a proposed replacement by measuring from the present facility as a base.

Reverting to the example of single-machine replacement on page 31 (the principle is of course the same for the replacement of groups of machines), suppose our operator wondering whether to renew his lease on machine *X* for another year is first approached by a rental agent for *A*. This agent is able to show an operating cost saving of $3,000 on a service of equal quality. He argues therefore that the operator can afford to pay for *A* a rent of $6,000, $3,000 higher than he pays for *X* but that since the rent is in fact only $5,000, the replacement yields a "profit" of $1,000. Next appears the rental agent for *C*, who demonstrates an operating cost saving over *X* of $5,000, and in addition a service superiority of $1,000. By his reasoning the operator can afford for *C* a rent $6,000 higher than he pays for *X*. The actual margin being $4,000, the "profit" from replacement is $2,000. The operator, in other words, is getting for a rent of $7,000 a machine for which he could afford to pay $9,000. Presently the agent for *B* turns up. In his case the saving of operating cost is $6,000, and the service superiority $500, indicating that our

operator can afford a rent $6,500 above *X*, or $9,500. The actual rent being only $7,000, he is in the velvet on the replacement to the tune of $2,500.

Now all this easy "profit" from replacement—$1,000, $2,000, and $2,500 for *A*, *C*, and *B*, respectively—may be quite exciting to our lessee until he begins to collect his wits. He then realizes that these sums represent simply the excess of what it is alleged he can "afford" for these machines over and above what it actually costs to rent them. Thus, it is said, he can afford to pay $6,000 for *A*, which rents for $5,000; $9,000 for *C*, which can be had for $7,000; and $9,500 for *B*, which is available also at $7,000. Obviously this is preposterous. If he operates his business, as he should, with a view to keeping his costs at a minimum he cannot "afford" to pay higher rents than the market asks. Even less can he consider such overpayment a "profit."

This grotesque perversion of reason and common sense is a result of measuring the *superiority* of *A*, *B*, and *C* over *X*, the worst of the four machines, rather than the *inferiority* of *A*, *C*, and *X* as compared with *B*, the best machine. If we make the latter comparison, we can readily compute the highest rent our operator can afford to pay for each. This is the rent that equalizes total cost (adjusted for differences in quality of service) with the total for *B*. Obviously, it is $3,500 for *A*, $6,500 for *C*, and $500 for *X*. Since the market rentals are $5,000, $7,000, and $3,000, respectively, the *loss* in using these machines while *B* is available is $1,500, $500 and $2,500, in order. They are under water by these amounts.

We are reminded of a certain architect encountered by Gulliver in Balnibarbi, a close observer of the bee and the spider, who had contrived, in emulation of these insects, a new method for building houses, beginning with the roof and working downward to the foundation. While the erection of buildings by this procedure is attended by certain practical difficulties, the architect would have been on solid ground had he advocated the same basic approach to the problem of replacement. *For here all valid measurement is from the top down.*

In the firmament of mechanical alternatives there is but one fixed star: the best machine for the job. This is the base point and standard for evaluating all others. What an operator can afford to pay for any rival or competitor of this machine must therefore be derived by a top-down measurement. *But the process is not reversible.* He cannot properly compute what he can afford to pay for the best by measurement upward from its inferiors.

THE PRINCIPLE APPLIED TO LONG LEASES

When capital goods are rented for a short period, it is permissible to ignore the possibility that the best facility currently available for a particular job may yield that position during the lease. This is not ordinarily permissible, however, when the lease extends over a long period. *In this case it is essential to allow at the outset for the appearance of better alternatives during the life of the contract.* When and as these appear, it will be necessary, in accord with the top-down principle, to compute by comparison with them the rent economically payable on the present facility. Thus the facility may be subject as time goes on to comparison with a whole succession of alternatives, each better than the last.

Suppose we have the same line-up of possibilities for next year shown in our earlier example (page 31) except that the owner of machine *B* asks the prospective lessee to sign a 10-year lease. Because this machine, at a rental of $7,000, is the best available now, can the operator afford to commit himself for 10 years at this figure? As a rule, no. He must protect himself against a spectral array of machines and contrivances still unborn which will arise in the course of time to challenge this aging unit. He will probably find that to keep *B* competitive with the currently best alternative over a 10-year interval he must shade the rent downward periodically. If, therefore, he is to offer a schedule of annual rentals that will reflect what he can afford to pay year by year for *B*'s services, it will have to be on a declining scale of some sort.

That current rental value is normally downward over the service life of a machine is almost self-evident. To prevent such a regression it would generally be necessary that the service be unimpaired in quality to the last moment; that there be no advance in operating costs with age; and that there be no obsolescence. Here is a trinity of conditions seldom present simultaneously. It usually happens, as we found in the earlier discussion of functional degradation, that as time goes on new competitors rise to challenge existing facilities, offering a higher quality of service or lower operating cost, or both, while the challenged assets undergo a progressive deterioration from their own earlier performance. Hence the gap between the old and new widens and has to be offset in a competitive rental market by price concessions on the services of the old. The rentability of the asset is thus progressively eroded.[1]

If our hypothetical operator is able, from clairvoyance or past experience, to foresee year by year the decline in the rentability of machine *B* for his purpose, he can readily compute an appropriate schedule of annual rentals for the 10-year period of the proposed lease. Lacking this detailed prevision, he must either make a guess or rely on some kind of probability calculation.[2] But unless he pays his respects by one means or another to the principle of top-down measurement, he is likely to saddle himself for later years with a rent that reflects what he can afford to pay *now*. This is a sure way,

[1] This does not mean, of course, that rentability necessarily runs off in a smooth and regular course. For individual facilities, indeed, the progress of this descent is usually uneven, and often highly erratic. The factors that impair rentability—obsolescence, service deterioration, increased operating costs—do not operate smoothly in individual instances; their impact is characteristically more or less "lumpy." Thus an office building may begin suddenly to pay the penalty of obsolescence when a more modern competitor goes up in the next block. Or a bulldozer that has coasted along for years on light repairs may come up abruptly against the necessity for major renewals.

[2] A probability curve based necessarily on a large number of cases would of course iron out the individual eccentricities just referred to, yielding a reasonably smooth and orderly descent from the original $7,000 a year to something much lower at the end of the contract.

under normal conditions, to develop costs out of line with competition.[1]

II. Replacement of Ownership by Lease

We have been discussing some aspects of the replacement problem as it presents itself to a lessee of equipment, not, as we pointed out, because leasing is important in itself, but rather because it affords an indirect approach to the problem of ownership replacement. It is a means of wading, rather than plunging, into the subject. We can exploit this flanking attack somewhat further, if we wish, by considering next the case of mixed replacements, that is to say, replacements that involve a switch from ownership to rental or from rental to ownership. Suppose we start with the former.[2]

We have the owner of a machine, let us say, who wishes to appraise the possibility of replacing it by another obtained in the rental market. After a canvass of the situation, he finds three apparently eligible possibilities, on which he goes to work with a sharp pencil. How shall he set up the comparison? Obviously, he must estimate for next year (assuming the rental equipment is available on a one-year lease) all differences among the several machines in operating cost and value of service. Obviously, also, he must charge the rent

[1] It should be obvious that if an operator must observe the principle of top-down measurement in appraising the rent he can afford to pay over the course of a long-term lease, the owner of leased facilities must do likewise in appraising the rentals he can hope to get over the service life as a whole. For he too must reckon with the probability that time will bring superior alternatives that will whittle down, by their competition, the rent his facilities can command. It matters not whether he can foresee the form and character of this evolution. Like an insurance company, he must deal in probabilities when he cannot predict in detail.

[2] We are assuming a situation in which, over a certain range of service requirements at least, it is about as advantageous to rent as to own, or vice versa, and in which, therefore, tenure is in fact divided between the two forms. For reasons discussed earlier, this situation is not too common in machinery and equipment, though it is frequently found in real estate. That the advantages of the two tenures in the mechanical field are occasionally fairly well balanced may be inferred, however, from their continued coexistence for certain types and items of equipment.

as a cost of the leased machines. But what should he charge as the capital cost of continuing his present unit in service for another year? Here he runs into trouble.

CAPITAL COST OF EXTENDING OWNERSHIP

Being a simple soul unversed in the mysteries of replacement theory, our operator is likely to recall that he bought the machine for $10,000 ten years ago, that he has been depreciating it at 5 per cent annually, or $500 a year, and that he has an unrecovered investment of $5,000. He is likely, therefore, to conclude that the annual capital charge—counting taxes, insurance, and the like as operating expense—is $500 for depreciation, plus interest on the remaining investment, which at 10 per cent (his figure, let us assume) is around $500 a year, a total of $1,000.

It may astonish our operator to learn that these figures have no direct bearing on the decision he confronts. By his devotion to history, as reflected in his books of account, he has violated unwittingly the first rule of replacement analysis, "Remember Lot's wife." For the retrospective glance that transformed her into a pillar of salt can convert this analysis into a fiasco. In reckoning the capital cost of an asset already owned, history is significant only as it casts light on the present or future; the past as such has no relevance whatever. For this reason data on the purchase price of the machine 10 years ago, the intervening depreciation accrued, and the unamortized balance of the account are meaningless save as they indicate what the asset is worth today and will be worth tomorrow—which they almost certainly do not. The machine might have been inherited, received by gift, or bought for a dollar, without altering the replacement problem one iota. It might have been depreciated on the books either completely or not at all, again without affecting the result. *Replacement comparisons are concerned with the future, and with the future only.*

It is obvious for this reason that the capital cost of an existing asset for replacement purposes is a radically different

animal from capital cost for accounting purposes. The accountant, like Lot's wife, cannot resist the backward look. His task, as he construes it, is to allocate over the service life of an asset, via the depreciation charge, a sum of money invested in the past. It is a process of amortization, or capital recovery. Essentially retrospective, it has no direct bearing on the replacement problem. To the replacement engineer, on the other hand, the original investment and the accounting amortization to date are (or should be) merely ghosts from the dead past. He can disregard entirely capital costs already incurred, save as they may indicate cost that must be incurred hereafter. Only the latter are directly relevant to replacement decisions.

Now an asset already owned may require further capital investment in the way of additions, betterments, or renewals. Such future expenditures are obviously a part of the capital cost of keeping it. There is another component of this cost, however, usually referred to in the economics textbooks as "opportunity cost." *It is the cost of foregoing the opportunity to sell.*[1] Money invested in the asset years ago is just a memory, but money offered for it today is real, and the cost of refusing it is a real cost. Indeed, in the absence of future capital outlays on the asset, it is the *only* capital cost properly chargeable against continued ownership and use.

What is the measure of this opportunity cost? Obviously, it consists of two elements: (1) the return obtainable during the period of comparison from the best alternative investment of the funds realizable from the sale of the present asset: (2) the loss in the sale value of that asset in the interval. Thus if the present sale value of our operator's machine is \$3,000 and if he can get a 10 per cent return from alternative investment, the first element is \$300. If the realization value is expected to be \$2,500 at the end of the year, the second element is \$500. The sum of the two is the amount that should be charged for

[1] As we shall see later (p. 126), it may also be the cost of foregoing the opportunity to use the machine on some other job or assignment in the same ownership. For the present we exclude this complication, however.

replacement purposes (in the absence of additional capital outlays) as the capital cost of continuing ownership for one year.[1]

Once our operator has grasped the distinction between capital cost for accounting purposes and the cost of extending ownership, he can cast up a reasonable comparison of the available possibilities for next year, which we shall suppose to be as follows:

	Estimates for next year			
	Present machine	Rental machines		
	X	*A*	*B*	*C*
Operating cost	$2,500	$2,500	$2,200	$2,000
Service superiority over *X* (subtract)	......	0	500	300
Rent	......	700	700	1,000
Cost of continuing ownership	800	......	......	......
Total cost, adjusted for service superiority	$3,300	$3,200	$2,400	$2,700

When he has studied these estimates, our operator can hardly be in doubt of the result. He will lose $900 next year by retaining his present machine when *B* is available. If *B* were not available, he could still take *C* with an advantage of $600 and could even gain slightly by taking *A*.

A POSSIBLE JOKER

If the replacement decision in this case could be made firmly and finally on the capital cost calculation just described, we should have to conclude that the replacement problem in a comparison of rented facilities with existing ownership is

[1] It follows, of course, that if the present asset has no sale value the capital cost of continued ownership is zero. In this case a rental machine must show a combined total of rent and operating cost lower than the operating cost alone on the incumbent (after adjustment, of course, for differences in the value of the service rendered).

closely similar to the problem in all-rental comparison, as developed in the preceding section. The only difference, apparently, is the insertion of an estimated figure for the capital cost of retaining the owned asset over the period of comparison in lieu of the known figure for rental cost used in the analysis of the lease alternatives.[1] Unfortunately, however, it is not always so simple.

Granted that our operator's estimates for next year are well grounded and that he can gain $900 over that interval by selling his present machine and leasing *B*, he must nevertheless look beyond the period to be sure the shift is justified. For in disposing of his asset he is selling a stream of future services that is not coterminous with the lease. The machine may be physically good for many years more. It is not sufficient, therefore, that the best alternative to continued ownership be superior over the next year only; this superiority (and any continuation thereof after the close of the period) must not be canceled out by subsequent inferiority.

If our operator were clairvoyant, he might extend his calculations over the entire future career of the existing equipment, testing not only the next year but the remainder of the service life as well. By matching the unit in this way against a long succession of challengers— many of them not yet in existence— he could draw a year-by-year schedule of gain and loss from a shift to the rental market and could say definitely whether the gain of $900 over the next year would be offset by subsequent loss.[2]

But clairvoyance is a rare gift with which, unhappily, our operator is not endowed. Seeing the future "as through a glass, darkly," he can only guess, with fingers crossed, whether the gain for the next year from replacing with *B* will hold in

[1] As noted earlier, capital cost is exclusive of maintenance, taxes, insurance, and the like, while rent may or may not include such items. Where they are so included, the figures for operating cost under the two tenures are not strictly comparable.

[2] Because future gains and losses are discounted in the present, it would of course require more than $900 of remote disadvantage to offset the $900 of nearby advantage. The development of this point must be deferred for the moment.

favor of the best alternative to ownership in the following period, or in the ones after that. If he rejects such long-range guessing as impossible, he must be reminded that in reality he cannot avoid it. For a decision to sell out and to lease *B* for one year rests implicity on the assumption that the $900 gained in that interval will not be offset later by a reversal of advantage. Contrariwise, of course, a decision not to sell implies the assumption that there will be such an offset.

While either decision involves an explicit or implicit judgment on the hazard of a reversed advantage after sale and while either appears therefore to call for long-range prevision or forecasting, the situation is likely to be less difficult in practice than it seems in theory. If the year chosen for the comparison is fairly representative (involving a normal rate and character of operation, normal maintenance, and the like), the appearance of a decisive advantage of rental over ownership gives sufficient assurance in most cases that the displaced facility would not "come back" by successfully challenging the best alternative of some later period, to say nothing of offsetting through this restoration of supremacy its disadvantage in the meantime. As a rule, facilities displaced from a given service or function do not "come back." Nevertheless the hazard remains, and our operator must appraise it to the best of his ability.

III. Replacement of Lease by Ownership

Having considered the problem of an owner contemplating a replacement through the rental market, let us now reverse the situation. This time our operator has been renting, but wishes to survey the advantages of owning his own equipment.

Let us suppose that after surveying the market he has come up with the best machine for his purpose currently purchasable. It costs $10,000. So far, so good. But in opposing this possibility to the alternative of continued rental he is at a loss to know how to line up the comparison. He can get quotations on a one-year lease at $3,000, but the proposed

unit, if he buys it, will last many years. How can the two be commensurated?

The answer is that they *cannot* be commensurated as they stand. For any comparison of alternatives must cover the same span of time. If the choice is between buying now and renting for the life of the proposed purchase, the rental alternatives must be projected over that interval. If it is between buying now and buying somewhat later, with rental during the period of deferment, it may be necessary to envisage the future even further ahead. In either case our operator is plunged, willy-nilly, into long-range crystal gazing.

DISCOUNT FOR FUTURITY

This brings him at once to a problem common to all replacement analyses involving long-range forecasts, the adjustment for differences in the *timing* of the advantages and disadvantages to be compared. For the alternatives normally involve flows of receipts and expenditures differently spaced over time; we are compelled, therefore, to commensurate magnitudes of unequal futurity. Obviously, if there were no discount for futurity, this would in no way complicate the calculation. The question of timing could be simply ignored. But the future *is* discounted, as a matter of fact, in all societies of which we have knowledge. This discount is reflected in a time perspective not unlike the space perspective with which we are visually familiar. The more distant an object in space, the smaller it appears; the more distant an event in time, the less its "present worth."

Why is the future discounted? This is no place, obviously, for an extended discussion of the problem, but a few passing observations may be of interest. First of all, the market in which present and future benefits are commensurated is made up of short-lived human beings, inclined, as a rule, to place a lower valuation on benefits accruing after they are dead than on those enjoyable during their lifetime. Secondly, there is a limit to the foresight and providence of most people

even as to future benefits that fall within their own life expectancy. The impulse to enjoy now is powerful with the great majority, and with many it is overwhelming. The collective willingness or capacity of society to maintain present values for future benefits—at the cost of foregoing present consumption—is therefore limited.

So limited is it that in all modern economies, at least, future benefits are bought and sold below par, that is to say, at a discount. The supply of such benefits (the unconsumed services of all existing durable goods plus other presently purchasable future values) exceeds the capacity of the market to maintain them at par. This is not surprising; on the contrary, it is inevitable. The ultimate realization value of all future benefits outstanding is simply too large to be carried as present worth. Witness the fact that a single asset with an unlimited series of such benefits—a diamond or a perpetual bond—would have if undiscounted an infinite present value.

The existence of discount is due also to another factor. The future is less certain than the present. Anticipated benefits may not be realized when the time comes; hence they are discounted for uncertainty and risk, in line with the old maxim that "a bird in the hand is worth two in the bush." When the hazard of nonfulfillment is present, it requires the prospect of a larger bird, if not two birds, to balance the one in hand. Thus we would have discount because of risk even if known and certain future benefits were valued at par. In practice, discount reflects in varying combinations both the effect of risk and the incapacity of the community to carry at par all the future benefits in the market.

Whatever the causes of the discount for futurity, its existence requires that all present and future magnitudes involved in replacement analyses be brought to a common time reference for comparison. This can be done by expanding them at compound interest to the same point in the future, by reducing them at compound discount to the present, or by converting them to "uniform annual equivalents"—

in other words, to time-adjusted annual averages.[1] Since we live in the present, this is the time reference of greatest significance, and ordinarily comparisons are made in terms of present worths or of present uniform annual equivalents.

Later on we shall devote a chapter to the question of what the interest rate should be in replacement analyses; here we are concerned only with the principle that interest should be charged whenever an extended future is involved. Once this principle is established, any conventional rate can be used for illustrative purposes.[2]

HYPOTHETICAL CASE

After this digression we return to our machine operator confronted with the problem of replacing rental by ownership. We shall give him short shrift, however, for his problem is not only too difficult for comprehensive treatment in this "warming-up" chapter, already grown long; it is so similar to the problem of replacing ownership by ownership that for most purposes we may just as well attack the latter directly.

[1] Interest is, of course, discount in reverse. When future benefits are discounted to the present, they yield when realized an increment over their acquisition cost equal to interest on the unrecovered portion of that cost at the rate of discount. If we pay $90.91 for $100 realizable a year hence, reflecting a discount of 10 per cent, the $100 when received yields a return of capital and 10 per cent interest on $90.91. Or if we buy for $614.46 an annuity of $100 a year for 10 years, again discounting at 10 per cent per annum, the receipt of the annuity will return the investment with 10 per cent annually on the currently outstanding balance. We can state the relation of interest to discount by saying that if future dollars exchange at less than par for present dollars (are discounted) the latter necessarily must exchange at more than par for future dollars (must yield interest).

[2] To avoid a possible misunderstanding, it may be well to anticipate later discussion to the extent of a comment on the argument sometimes encountered that because interest on equity capital is not considered a cost for accounting purposes it should be disregarded in replacement studies. This contention is of course quite mistaken. The accountant's distinction in the treatment of borrowed and owned capital is irrelevant here. If a replacement financed by loan funds must yield benefits sufficient to return the investment with interest, so also must a replacement financed by equity funds. For, as we have seen, equity money has alternative uses. It can earn a return elsewhere. Its "opportunity cost" is therefore just as real as the contractual cost of interest on a loan and is just as valid and necessary a charge against replacement investment.

It is instructive, nevertheless, to consider one highly simplified case before taking leave of rental-ownership replacement.

Our operator, we have said, can buy a new machine for $10,000. Suppose for the sake of simplicity, that he excludes the possibility of buying at some later time, and that his choice is therefore between (1) buying now and using the same machine for several years or (2) using over a like period of time a succession of different machines obtained on annual lease in the rental market. Suppose further that the machine considered for purchase is identical with the one he is renting this year for $3,000. If the applicable interest rate is 10 per cent, can he afford to buy?

To answer the question even in this simplified case the analyst must estimate (1) the future course of rentals, and (2) the future operating inferiority of the purchased machine as compared with the best machines available in the rental market. Since the owned machine will of course age on the job, accumulating deterioration and obsolescence as it goes along, it will necessarily become inferior, operationally, to the succession of newer units obtainable by lease. Let us say our operator estimates that the annual rental will continue at $3,000 and that the owned unit will accumulate operating inferiority relative to its successive rental alternatives at the rate of $300 a year.[1] The question then becomes: "Is there any period of service for which the proposed acquisition will show a time-adjusted annual average of capital cost *and* operating inferiority less than $3,000?" If so, purchase is indicated; if not, rental. The solution is shown on page 47.

It is evident that there is a considerable range of service lives for which the proposed machine will show an annual average of capital cost and operating inferiority below the assumed rent on leased machines ($3,000) the best period being 10 years, with an average of $2,745. It appears, therefore, that replacement of rental by ownership is advantageous.

[1] The operational difference is of course exclusive of capital costs on both sides of the comparison, capital recovery and interest on the owned asset, rent on the leased assets. It is assumed here that the rent is pure capital cost—in other words, that all operating costs are borne by the lessee.

Year	Operating inferiority of owned machine in year indicated	Average inferiority for period ending with year indicated[a]	Average capital cost for period ending with year indicated[b]	Combined average for period ending with year indicated
1	$ 0	$ 0	$11,000	$11,000
2	300	143	5,762	5,905
3	600	281	4,021	4,302
4	900	414	3,155	3,569
5	1,200	543	2,638	3,181
6	1,500	667	2,296	2,963
7	1,800	787	2,054	2,841
8	2,100	901	1,874	2,776
9	2,400	1,012	1,736	2,748
10	2,700	1,118	1,628	2,745
11	3,000	1,219	1,540	2,759
12	3,300	1,316	1,468	2,784

[a] This and the other averages are uniform annual equivalents; that is to say, they are averages of the data to which they relate, *after adjustment for interest.* A word about these annual equivalents. Two series of future magnitudes may have the same time coverage and the same aggregate amount, thus yielding identical annual averages as ordinarily computed; but if their time distributions diverge, their time-adjusted averages are different. Consider the following:

Year		
1	$ 500	$ 100
2	400	200
3	300	300
4	200	400
5	100	500
Total	$1,500	$1,500

The simple averages of these series are the same, $300 a year. Their uniform annual equivalents, or time-adjusted averages, at 10 per cent interest, are $319 and $281, respectively. These are the level annuities which are equivalent in each case to the original series *when interest is taken into account.* The use of uniform annual equivalents is commonplace in engineering economy studies, and is discussed in any textbook on the subject. See, for example, Eugene L. Grant, *Principles of Engineering Economy*, rev. ed., Chaps. 4 and 8, The Ronald Press Company, New York, 1938.

[b] Assuming no salvage value at any time.

This example is interesting from various standpoints, but we shall content ourselves with two comments: First, it illustrates the principle of top-down measurement. The operational *inferiority* of the owned machine is derived by comparison with the best alternative currently available

(in the rental market). Second, it indicates the extreme complexity of replacement analysis when ownership is involved. Here we have simplified the case by ruling out, quite unrealistically, the possibility of purchase at some time in the near future, narrowing the choice to buying *now* or renting for another 10 years (the best service life of the proposed machine). In practice our operator can buy now, a year from now, two years hence, or at any other time, and this possibility must somehow be taken into account. We have simplified the case in other ways. But even so the forecasting required is onerous. The analyst must not only predict the course of rentals 10 years ahead; he must appraise the future competition of rental machines *that do not yet exist.*

It is one thing to trade the current services of capital goods in the spot market; it is another to deal in futures. A replacement involving ownership, being a transaction in future services, demands inescapably an evaluation of remote costs and benefits and their commensuration with others present and future. It is a decision calling by right for the prescience of the gods, yet made perforce by mortal men. Peering myopically into the mists of the future, they must guess and guess again, responsive to the prompting of their bones, hoping against hope they are not too wide of the mark. We cannot ask that men be gods, and have divine foreknowledge, but we can ask an understanding of the problem that would enable them to reach correct replacement decisions *if such foreknowledge were vouchsafed.* Such understanding, as applied to replacements under user ownership, we hope to develop in the succeeding chapters.

Chapter IV

THE PROBLEM OF PREDICTION

We have been working our way gradually into the intricacies of replacement analysis through the consideration of rental and rental-ownership alternatives. As indicated at the outset, we have given attention to rental replacement, not primarily because of the practical importance of this form, but rather because it is possible in this way to establish with greater ease and in a simpler context certain principles and propositions common to all replacement analysis. With this accomplished, it is now time for a frontal attack on the real subject of our study, replacement under user ownership.

We begin this attack by considering in the present chapter an aspect of replacement analysis of little concern to the operator of equipment on short lease but of primary importance in ownership replacement—the problem of prediction. This is a problem on which we have thus far touched only lightly and incidentally (in connection with rental-ownership replacements) and which it is necessary now to explore more systematically. For it is above all the predictive requirements of ownership replacement that make the analysis difficult. Hence the importance of understanding clearly what these requirements really are.

A THEORETICAL INQUIRY

It may be appropriate to warn the reader again that we are still in the realm of "pure theory." The theory is "pure" in the sense that it is not practically applicable as it stands. For it is essentially an exploration of how we should make replacement decisions *if we had complete foreknowledge of all factors affecting them.* The practical problem, obviously, is to

make decisions without such foreknowledge, and any usable replacement formula or device must take account of this necessity. But the fact remains, as we said in the preceding chapter, that unless we understand replacement analysis as for the gods we are at a loss to judge the practical expedients which mortal men must substitute, of necessity, for divine prescience.

As the Foreword makes clear, we are not interested here in theory for its own sake. However remote the heights we must ascend in the course of the inquiry, and however rarefied the air, the objective is strictly mundane. We hope to descend from the clouds not only with practical simplifications of celestial replacement analysis but with a touchstone for assaying some of the formulas, shortcuts, and rules of thumb in current use. Obviously, before we can simplify anything we must first understand what it is we are simplifying.

We said a moment ago that theoretically a correct replacement analysis would take into account all factors affecting the decision, however remote in time. Let us begin by asking how far into the future such an analysis would have to penetrate.

THE DURATION OF CONSEQUENCES

It is an old Sunday-school platitude that the consequences of today's actions run forward to the end of time. The effects of each little deed, the moral runs, expand like the ripples from a pebble in the ocean, leaving the universe everlastingly different, in some degree, than it would have been had other deeds been done. Doubtless this is as true of equipment decisions as it is of others. It does not follow, however, that the analyst, even if he could, should chase the consequences of his available choices out to the fringes of time and space. For he has no concern, presumably, with consequences outside the boundaries of the business enterprise he serves or beyond the anticipated life of that enterprise. This shortens his perspective decidedly.

Even within these limitations, however, the consequences

of equipment choices may run forward over a long period. It may seem at first glance that the decision to purchase a machine involves the future only to the end of its service life, which is to say that the consequences of the decision are exhausted during this interval. But this view is mistaken. If the enterprise to which the machine contributes goes on indefinitely (as it ordinarily does in expectation) the consequences of the purchase may run far beyond the period of service. This is because the purchase involves the choice not only of the machine itself but also of its *successors*. Its acquisition determines the available options of the future. For if the machine has an economic life of 10 years, that fact determines the best alternative available at the time of its replacement. The identification of this second machine in the line of succession in turn identifies the third. The selection of the third determines the fourth, and so on. *A decision to buy is therefore a decision in favor of an entire succession of future replacements.*

This proposition deserves particular emphasis. Mechanical alternatives cannot be appraised on their own merits alone. They are like comets trailing their tails after them, the tail being in each case the best replacement succession the machine makes possible. To put it otherwise, each alternative carries with it options on its best sequence of future replacements and is traded with these options, not separately. It follows, as a theoretical proposition, that the consequences of a decision run for the life of the sequence, which may embrace any number of mechanical generations from one upward.

THE DURATION OF DIFFERENCES IN CONSEQUENCES

Replacement analysis always involves the comparison of specific mechanical alternatives.[1] For this reason it is con-

[1] This is true whether the analysis makes a simultaneous comparison of a number of possibilities or compares them successively two at a time. The latter is the more usual procedure. On this point one authority observes: "In engineering practice there may be many alternatives; in fact the important part of the engineer's job sometimes is to hunt for other alternatives than those which have been considered. However, the principles that apply in comparing two alternatives will apply to any number. Even though there are many alternatives to be considered, it is often most convenient to consider them in pairs, making succes-

cerned only with *differences* between these alternatives (including their replacement successions). It is the duration of these differences, therefore, not the life of the successions themselves, that determines the necessary time span of the comparison. For obviously no comparison of alternative successions need be carried beyond the point, if any, at which the subsequent consequences are common to both.[1]

This point is reached when replacement occurs at the same time in both successions, thus yielding identical future choices and possibilities from there on. If, for example, present mechanical alternatives *A* and *B* have alike a 10-year service life, offering therefore the same options at the end of the period, the comparison of their advantages and disadvantages can properly be confined to 10 years. Or if *A* has a 10-year life while *B* and its first replacement have 5 years each, *A* can correctly be compared over 10 years with two generations in the *B* sequence. Again, if *A* is good for 10 years and *B* for 15, with similar life expectancies for their successors, three generations in the *A* series can be compared over a 30-year period with two generations in the *B* series.[2]

THE SPAN OF PREDICTION

This illustration may seem to suggest that when the necessary span of *comparison* is limited by a common cut-off date there is a like limit to the necessary span of *prediction*. This can be true, however, only when the period of comparison

sive eliminations of the less economical ones." (Eugene L. Grant, *Principles of Engineering Economy*, rev. ed., p. 21.)

[1] The logical purist may insist that if the two successions have common consequences after a certain point, the choice of one rather than the other has *no consequences whatever* beyond that point, although the choice of either may have consequences as against a third alternative. Applied more broadly, this means that if there is a point beyond which *all* possible choices have identical results, that point is a terminus to the consequences of *any* choice. Obviously, we are dealing here with a matter of definition. We can define the consequences of a choice either in terms of what follows after it or in terms of *differences* between what follows it and what follows other choices. We use the former definition, but our conclusions can easily be restated in terms of the latter.

[2] We are taking for granted here, for purposes of illustration, that the correct service lives are known in advance. As we shall see later, the prediction of service life is itself highly problematical.

may be ascertained *without looking beyond it.* If the service lives of successive mechanical generations are determined by purely physical causes, such as the natural decay of a railroad crosstie or a fence post, the identification of the earliest replacement date common to two or more successions does not require knowledge of the future beyond that date. But if these service lives depend on economic factors, the answer is different. In this case the correct life of one machine in the sequence can be ascertained only when the life of its successor is known. This in turn can be found only when the life of the next following unit is given, and so on to the end of the sequence. When we are dealing with economic replacements, therefore, the theoretically necessary span of prediction remains the entire life of the succession, even though the period of comparison, once determined, may be shorter. Since most replacements are made, in part at least, for economic reasons, it is evident that there are comparatively few cases in which the span of prediction can be abridged.

While it is usually necessary, in theory, to see ahead to the end of the mechanical sequence involved, this necessity is profoundly modified in practice by a factor discussed in the preceding chapter, the discount for futurity. In a market where the future is discounted, the present worth of remote gains and losses becomes so negligible that it might well be disregarded even by a replacement analyst endowed with complete foreknowledge. At a discount rate of 10 per cent per annum, for example, the present value of $1 payable 50 years hence is less than 1 cent. At a 5 per cent rate, it is only 9 cents. Obviously, the only consequences of replacement decisions that need seriously concern the analyst are those appearing in the reasonably near future—the period, that is to say, within which they have a significant present worth. Thus we can brush aside, as a practical matter, any theoretical requirement for the prediction of the remote future.

This may be a comforting thought, but it does not get us very far. For even with due allowance for discount, it is still necessary, as a rule, to see more of the future than any mortal

can. This will be evident when we have taken a closer look at the nature of replacement analysis.

A CLOSER LOOK AT REPLACEMENT ANALYSIS

What we have said thus far about the duration of consequences and the span of prediction, applies to *any* equipment decision, whether it concerns original installation or replacement. There are certain peculiarities about the predictive requirements for replacement, however, which need further attention.

A replacement analysis consists, obviously, of two separate and distinct operations. The first is the selection of the "challenger," that is to say, the best unit or group of units now available for the replacement of the incumbent, which we may call the "defender." The second is the determination of whether the challenge is valid, in other words, whether the defender is presently replaceable.

The first of these operations, the selection of the challenger, does not differ in any essential respect from the selection of the best equipment for an original installation. While it is theoretically necessary in either case to take account not only of the presently available machines but also of their best replacement successions, these machines, if installed, can usually defend their tenure for several years at least, hence differences between their successors are significant only for the comparatively distant future. Because of discount, these differences are of course greatly diminished in terms of present worth. It follows that the importance of their correct prediction is correspondingly diminished.

It is otherwise, however, when we turn to the second operation in the replacement analysis, the challenge itself. Here we have a contest between the finalist in the elimination series for challenger on the one hand and the defender on the other. The latter, unlike the former, cannot be presumed to have ahead of it a long life on the job; indeed the very existence of the challenge raises the question whether it has properly any further life at all. The problem of the challenger's suc-

cession may be 10 or 20 years away, but the problem for the defender is immediate. For this reason, differences between alternative replacement successions are not diminished by the magic of discount, and their correct prediction becomes much more important.

Let us consider for a moment what the alternatives for the defender's succession really are. It may seem at first glance that the challenger, having eliminated other contenders for the privilege of making the challenge, is now the only claimant in the field, hence that the challenge itself is a duel with only two participants. This is not the real situation, however. It is true that the challenger has eliminated all *presently available* rivals. But it has not eliminated *future* rivals. The latter, though at present mere potentialities, are important figures in the contest. For the current challenger can make good its claim to succeed the defender only *when there is no future challenger worth waiting for*. It must engage, as it were, in a two-front war, attacking on one side the aged machine it hopes to dislodge and on the other an array of rivals still unborn who also hope to dislodge the same aged machine, but later.

The point just made can stand emphasis, for replacement analysis is often conducted as if it involved only a two-handed duel between the current challenger and the defender, the challenger's future rivals being ignored. A good example may be found in analyses which compare challenger and defender over the full prospective service life of the former. The difference between the challenger's performance over its lifetime and the performance that would be obtainable from the defender *if it were retained in further service over the same period* is ordinarily of no significance whatever. Even if the defender is physically capable of service over the full life of the challenger—which it often is not—the real choice that confronts the analyst is not between retaining it for that interval or replacing it now; it is between *replacing it now or replacing it later*. It is a choice, in other words, between taking the current challenger or retaining the existing asset, not

10 or 15 years, but only until a more successful challenger comes along. That may be 1 year hence, 2 years, or 5.[1]

We can illustrate by assuming, for the sake of simplicity, that the present challenger and all machines hereafter available will have a service life of 10 years. Under these circumstances, the analyst confronts among others, the following possibilities:

1. He can install the present challenger and buy replacement machines at the beginning of years 1, 11, 21, 31, etc.
2. He can keep the defender 1 more year and replace at the beginning of years 2, 12, 22, 32, etc. Here he replaces with the challenger available a year hence.
3. He can keep the defender 2 more years and replace at the beginning of years 3, 13, 23, 33, etc. This option gives the nod to the challenger available 2 years hence.

These are only three among a large number of possibilities, but they suffice to exemplify the real nature of the operation we have dubbed the challenge. It presents a choice between the mechanical succession headed by the present challenger and various successions headed by the defender pending its displacement by a challenger of the future. Clearly, the issue cannot be decided without reference to the character of these future challengers.

There is an important corollary of this last proposition. Since future challengers must be considered, as well as the

[1] It will be recalled from the preceding chapter that we simplified the case of the rental operator contemplating ownership by narrowing his choice to purchasing now or continuing to rent for the full service life of the present challenger. The exclusion of rival challengers of the future is wholly unrealistic, as we pointed out at the time. Our operator can be sure it is advantageous to buy now only when he has determined that this is better than renting for any shorter period than the life of the current challenger and buying at the end of that period. His problem is similar, therefore, to that of the analyst in a straight ownership replacement. The only difference is that he must compare mechanical successions beginning with the use of rental units for various periods of years and followed by purchase, while the ownership analyst compares successions beginning with various periods of continued service for the presently owned machine and also followed by purchase.

replacement successions of all challengers, whether present or future, it follows that *there is no determinable relation between the current challenger and the defender that alone and by itself can justify a present replacement.*

Let us illustrate: Suppose, for example, that the challenger costs $10,000 and has a current operating superiority over the defender of $2,500 a year. Is replacement indicated? If the challenger's future successor can displace it in 5 years, the answer may be one thing; if it can displace it only after 15 years, the answer may be something else. Or if a rival challenger of comparable quality will be available next year for $8,000, the verdict may be different than if it will cost $12,000. The answer may differ, again, depending on the rate of improvement of future challengers over the current one. Clearly the present replaceability of the defender turns on these future developments no less than on the characteristics of today's challenger.

FORECASTING GHOSTS

It is evident from the foregoing that the predictive requirements of replacement analysis extend far beyond the forecasting of the future performance of presently available machines. The analyst must appraise also a series of machines *not now in existence.* If it is permissible so to describe the potentiality of devices still unborn, these machines are ghosts.

Ghosts though they be, it is impossible successfully to exorcise them. For since the choice between living machines can be made only by reference to the machines of tomorrow, the latter remain, whether we like it or not, an indispensable element in the calculation. It may be said, indeed, without too much exaggeration, that the appraisal of the ghosts involved is the heart of the replacement analysis. No replacement theory, no formula, no rule of thumb that fails to take cognizance of these ghosts and to assess their role in the play can lay claim to rational justification.

Now obviously it is impossible as a rule for mere mortals actually to foresee the form and character of machines not

yet in existence. In some cases, no doubt, closely impending developments may be more or less dimly discerned and so may be weighed, after a fashion, in the replacement analysis, but in no case can the future be penetrated more than a fraction of the distance that is theoretically necessary for an exact, or even a close, solution of the problem. What then is the answer? *Since the machines of the future cannot be foreseen, their character must be assumed.*

It is a cardinal defect of most replacement formulas that they fail to make clear their assumptions as to these future machines. Often these assumptions are merely implicit in the formula, without clear recognition by the analyst himself. Especially is this true in the case of popular rules of thumb. These devices have simply evolved over the years, by contact and imitation, as a kind of industrial folklore, never deliberately contrived, never clearly rationalized. If they can be said to make certain assumptions as to the future—and presumably there is *some* pattern of events in each case for which they would produce the correct answer—these assumptions are something read into them after the fact, of which the creators of the rules were unaware. This is true not only of rules of thumb, however. As we shall see later, even reputable and widely accepted "highbrow" formulas may contain unstated assumptions so patently unrealistic we can only infer that their authors were unaware of them.

Failure to recognize the predictive assumptions implicit in a replacement procedure is certain to lead to fuzzy thinking and mistaken conclusions. What is implied as to future developments? For what pattern of events does the procedure yield the correct timing of replacement? These hidden postulates must be brought into the open, where their reasonableness and probability can be evaluated.

Since the machines of the future must be taken into account, even though unpredictable, and since we must therefore deal with them by assumption, the problem, obviously, is to make the most reasonable and realistic assumptions that we can. It is essential, moreover, to do this openly and

explicitly, so that the replacement analyst can appraise the results arrived at by their use with full knowledge of what is involved. We propose, therefore, to construct a standard pattern or framework of assumptions as to the character of future machines. This is the task of the next chapter. Thereafter we shall explore the consequences of these assumptions for replacement analysis.

Chapter V

TWO STANDARD ASSUMPTIONS

We stated in the preceding chapter that while the challenger is by definition the best *existing* machine to contest the defender's job, it is still beset by rivals in the machines of the future. We added that because of these rivals there is no determinable relation between challenger and defender that by itself can justify a present replacement. Before we can test the validity of the challenge, we must fix, by prophecy or by assumption, the relevant relations between the current challenger and its future rivals.

It will be evident when we consider by what an impenetrable curtain future machines are shielded from our prevision that the cases are few and far between in which a specific prediction of their characteristics is possible. But this is only half the story. Even if he were willing to construct a forecast covering the necessary factors, the analyst would find himself bogged down in the most intricate mathematical calculations before he could deduce the consequences of his forecast for the replacement decision. As a practical matter, therefore, specific prediction is excluded for this reason if not for lack of foresight. *The best the analyst can do is to start with a set of standard assumptions and shade the results of their application as his judgment dictates.*

We have now to develop such assumptions. But this is easier said than done. For it is by no means self-evident what are the relations between future challengers and the present one that must be fixed by assumption, or how they fit together. The truth is we have not carried the inquiry thus far to the point where they can be identified. It is necessary, therefore,

to engage in further preparatory analysis before we can proceed.

THE CONCEPT OF OPERATING INFERIORITY

As we have stressed previously, almost any machine or piece of equipment is subject, as time goes on, to deterioration and obsolescence.[1] Deterioration is reflected in the decline, or retrogression, of its operating performance as compared with the performance that would be obtainable from an identical machine new. Obsolescence appears in the growing operating inferiority of such a replica of the existing unit in comparison with the best new machine currently available.

It is obvious that the relative importance of these factors varies widely from case to case. Some types of equipment are subject to heavy deterioration with age, but little obsolescence. Others suffer rapid obsolescence but little deterioration. It is obvious also that either may be variously composed as between differences in operating costs and differences in the quality or value of the service rendered.[2] In one case, deterioration may reflect an age-related rise in costs with little impairment of service; in another, the service may degenerate with little change in costs. Similarly, obsolescence may consist largely of cost obsolescence, or it may represent chiefly value-of-service obsolescence.[3] The combinations and permutations are legion.

[1] We use the term "deterioration" rather than "depreciation" because the latter is commonly employed to cover both wear and tear and obsolescence (or at least "normal" obsolescence).

[2] Since operating performance must be measured in terms not only of operating costs but also of the value of the service rendered, it is possible to analyze both deterioration and obsolescence into two components each. Thus deterioration consists of (1) the amount by which the operating cost of the machine in service exceeds the cost obtainable from the same unit new and (2) the amount by which the value of its service is below that obtainable from the same unit new. Obsolescence consists of (1) the amount by which the operating cost on a new replica of the machine exceeds the cost on the best alternative currently available and (2) the amount by which the value of the service rendered by this replica is below the value of the service of the best alternative.

[3] Among the factors producing value-of-service obsolescence is, of course, obsolescence of the product turned out with the equipment. Product changes often increase the inferiority of existing facilities relative to newer alternatives.

Whatever the combination of these factors, a gap opens up, with use and the passage of time, between the operating performance of a machine in service and the best performance obtainable from its current challenger. This gap is what we mean by operating inferiority. *It is the amount by which the machine is inferior, operationally, to its challenger.*

This gap may be considered, obviously, from three standpoints: (1) its *width* at a single moment of time, (2) its *contour* or course of development over a period of time, and (3) its *area* for the period. If its width is the operational difference between the machine and its challenger at one point of time, its contour is the shape described by a succession of such differences over time, while its area is the cumulative sum of the succession. Thus the area for any period in the life of the machine is the accumulated difference between the actual operating performance (considering both cost and service value) and the performance that would have been obtainable by using only the best services of the best machines available over the period.

It is important to emphasize that while the inferiority gap at any moment of time is the operational difference between two units, the machine in service and its current challenger, the contour and area of the gap are built up over a period of time by a sequence of comparisons between *different* machines. The machine in use is measured as time goes on against a changing series of alternatives, the best performance of each successive challenger being taken, for the period of its tenure of the challenger's role, as the basis of comparison. Thus inferiority is reckoned from a *moving* standard or target.

While this is only a brief and preliminary description of the concept of operating inferiority it will suffice for our present purpose, the formulation of standard assumptions. Before we can state these assumptions, however, we must develop a second concept which depends on the first, namely, the adverse minimum.

THE CONCEPT OF THE ADVERSE MINIMUM

Suppose now we consider a hypothetical question. What would be the proper equipment policy if capital goods were available free? The answer is obvious. Equipment would be replaced with great frequency, generally once a year or oftener. With this high turnover, we should have continuously a state of "perfect" or "total" mechanization, yielding at all times the very highest operating performance the technology is capable of. But unfortunately machines are not to be had for nothing. They cost money, a fact which precludes the attainment of this state of technological blessedness. For when their cost is taken into account, mechanical perfection can be no longer the exclusive goal of equipment policy. The analyst has to choose between more capital cost with less imperfection or less capital cost with more imperfection.[1]

Now when we have alternative magnitudes, each of which is adverse, the best we can do is to find the proportion or combination of the two which minimizes their sum. This proposition is the key to correct equipment policy. *It is the policy that minimizes the time-adjusted sum or combined average of capital cost and operating inferiority.*

This brings us to the concept of the adverse minimum. Since the operating inferiority of a machine relative to its best current alternative tends to increase with age, as indicated earlier, it is obvious that the time-adjusted average of such inferiority over the service life also tends to increase as the life is extended. It is equally obvious, on the other hand, that the longer the period of service over which capital recovery is spread, the lower is the average capital cost for the period.

[1] It will be noted that the point from which we measure operating inferiority is not the absolute mechanical perfection that would be obtainable if machines were to be had free; it is the performance of the best alternative when machines carry their existing capital cost. The best alternative in the absence of capital cost, when the object would be to minimize operating inferiority alone, would differ materially from the best in real life, when the object is to minimize the *sum* of capital cost *and* inferiority. Obviously, it is the best machine in real life that we must use as a standard.

Since one average varies directly with the service life and the other inversely, it follows that the sum of the two is itself a variable, with different values for different periods of service. The lowest of these values we call the "adverse minimum." *It is the lowest combined time-adjusted average of capital cost and operating inferiority obtainable from the machine.*[1]

As our purpose at the moment is simply to prepare the ground for the formulation of standard assumptions, we shall leave the further development of the adverse-minimum concept until later. To avoid misunderstanding, it is necessary, however, to point out that the adverse minimum is not an inherent property or attribute of a machine, but is relative to the particular job or assignment for which it is being analyzed. Since the operating inferiority of the machine may be different for each job, obviously it may have as many adverse minima as there are possible jobs.

FIRST STANDARD ASSUMPTION

With these preliminary explanations, we are now in a position to state our first standard assumption:

1. *Future challengers will have the same adverse minimum as the present one.*[2]

The first question, of course, is the basic justification for the assumption of repetition in this case. Is it reasonable to suppose that the present challenger's adverse minimum will be repeated indefinitely by its future rivals and successors? The answer to this question is another: Is any alternative assumption more reasonable? We know of none. In

[1] We refer here to the time-adjusted *average* of capital cost and operating inferiority rather than to their *sum*, because it is more convenient to compare averages than totals. Two machines or successions of machines are directly comparable with respect to the time-adjusted sum (present worth) of capital cost and inferiority only when they have the same time span. Their averages (uniform annual equivalents) are comparable, however, for different time spans. Since the determination of the adverse minimum of a piece of equipment involves the comparison of different periods of service, as we shall see in the next chapter, the definition of this minimum in terms of averages is clearly indicated.

[2] The reference is, of course, to future challengers for the job now under analysis and to their adverse minimum for that job.

general, when the future cannot be foreseen, the best we can do is to project a continuation of the present. All prediction rests, in the last analysis, on the premise that the past contains elements of recurrence or continuity that will repeat themselves hereafter. In the absence of evidence to the contrary, therefore, the presumption is in favor of repetition.

Even if repetition were no more probable, in general, than some specific pattern of nonrepetition we might select, it would still be by far the best standard assumption because of the unique simplicity of the replacement formula it makes possible. Not to anticipate discussion in the next chapter, we shall say here only that this consideration would be controlling even if the assumption of repetition were less justifiable on other grounds than it is. Given this justification, the assumption becomes inevitable.

SECOND STANDARD ASSUMPTION

While the assumption of repetition just developed is sufficient, as we shall see later, to fix the relation of future challengers to the present one and thus to banish ghosts from the replacement analysis, it does not suffice to yield a replacement formula that can be simplified for practical use. For despite the assumption that future challengers will repeat the adverse minimum of the present one, the analyst is still required to estimate for the latter the year-by-year course of inferiority accumulation, that is to say, the *contour* of the inferiority gap. We propose, therefore, a second assumption to obviate this requirement:

2. *The present challenger will accumulate operating inferiority at a constant rate over its service life.*

With this assumption, the analyst must estimate only one rate of accumulation instead of a different rate for each year of service. Here again we have what amounts to a methodological necessity. But here also we have the question of its theoretical justification. Suppose we consider this angle for a moment.

RETROSPECT AND PROSPECT

If we were to take annual observations on the growth of the inferiority gap over the lives of various machines, we should undoubtedly find that in most cases this growth is decidedly irregular, while in some it is highly erratic. There is every reason to believe that this irregularity is normal. The increase in operating costs with age rarely proceeds smoothly and evenly. There are breakdowns at varying intervals. Routine maintenance is punctuated by occasional heavy repairs. The decline in the quality of the service rendered is likely also to be uneven, at least in its economic consequences. Thus the service of a machine deteriorating in precision may be economically as good as new until the point is reached at which it can no longer maintain the required tolerances. Nor is the accumulation of obsolescence essentially different. Improvements in available alternatives, whether costwise or servicewise, usually come in spurts, with intervals of comparative stagnation between.[1] With all of these irregularities in its component elements, the inferiority gap itself can hardly expand smoothly.

We are speaking here, however, of the gap of an individual machine *as seen in retrospect*. But as we saw earlier, the replacement analyst is concerned with retrospection only as an aid to prediction. He must estimate the *future*. Does it follow from the irregularity of past inferiority accumulation that projections for the future must be equally irregular? By no means. The very fact that the course of accumulation is erratic in character and diverse from case to case argues against reliance on any individual history as a model for forecasts. What the analyst needs, obviously, is a projection based on the *average* experience of a large number of similar machines in similar service. For he confronts a problem not unlike that of an

[1] This becomes doubly evident when we consider the fact, noted earlier, that the obsolescence of productive equipment is frequently due to the obsolescence of the product it turns out. The development of the product tends also to proceed in spurts.

insurance company projecting the life expectancies of its policyholders. Both must play the averages.

Now it goes without saying that the analyst rarely has at his disposal even a fraction of the data required for a reliable experience table on the inferiority accumulation of like machines in similar service. He would need for a large number of such machines a comparison by year of attained age, between their performance at that age and the performance obtainable from the best alternative then available. Not only would this require operating records on the machines actually in service, it would call in each case for estimates of the performance of a series of units *not* in service. Playing the averages for projections of past patterns of inferiority accumulation, however desirable in theory, is therefore impracticable in fact, save possibly in the most exceptional cases. It is a counsel of perfection.

Since the inferiority gap is the sum of two components, deterioration and obsolescence, we can pursue the question of the reasonableness of our assumption of constant accumulation *as a projection for the future* by considering its application to the components separately.

CONSTANCY OF OBSOLESCENCE

We have already observed that the impact of obsolescence on individual machines in service is usually more or less "lumpy" or irregular, reflecting sudden changes in the product or improvements in the currently available alternatives. There is no reason, however, to suppose that such sudden changes are more likely to occur at one stage than another in the lives of the machines adversely affected. Overall, obsolescence probably represents a fairly steady and continuous pressure. From the standpoint of probability or prediction, therefore, unless there is special reason to deviate from the pattern in the particular case, the most reasonable assumption is that obsolescence is a risk spread indeterminately over time, hence that its incidence is random.

Now when we are dealing with occurrences spaced in random fashion over time, the best standard assumption we can make is that they will occur *at a uniform rate.* We can illustrate by analogy. It is impossible to predict which of the six faces of a die will come up on any particular throw, but it is possible to forecast that on 1,000 throws all will appear substantially the same number of times. Similarly, while we cannot foresee the time distribution of obsolescence in any one case, we can be reasonably sure that the average distribution for a large number of cases will approach uniformity. If we play the averages, therefore, as we must in the absence of prevision, we are justified in assuming that obsolescence will accumulate at a constant rate.

CONSTANCY OF DETERIORATION

While obsolescence develops as a result of factors external to a machine affected by it, the rate of accumulation being generally unrelated to the age of the machine, this is not true of deterioration, which is an internal phenomenon, clearly age-related. There is no theoretical presumption, therefore, that deterioration accumulates at a constant rate over the service life, even in terms of averages. It may be more or less constant, slow at first and more rapid later, rapid at first and then slower, slow at the extremes and fast in the middle, fast at the ends and slow in the middle, or otherwise. It may be lumpy or smooth. Here the question turns, not on the theory of probability, but on empirical evidence and common observation.

As we indicated earlier, deterioration is composed of two elements—the rise of operating costs above those on a new replica of the machine and the decline in the value of the service below that of the same unit new. As for the second element, probably much the less important of the two in general, we have no statistical evidence to offer. We do have, however, a limited amount of material on the course of one major age-related operating cost over the service life, namely, repairs and maintenance.

The chart on the next page shows smoothed trend curves (smoothed because of the limitations of the samples available) of annual averages of repair costs per unit of service, for eight classes of equipment: metal-working machinery, textile machinery, light trucks, intercity buses, locomotives, farm implements, passenger automobiles, and local buses. Service-unit repair costs are related in the first group of diagrams to the age of the machines in question, and in the second group to their accumulated use.

These trend curves, which presumably reflect fairly closely what the average would show for a large and representative sample of each type of equipment, display a general tendency for repair costs per unit of service to rise somewhat more rapidly in the early stages of service than later.[1] It is interesting to note, however, that whether these costs are related to age or to accumulated use, the curvature appears very mild.[2] It would be unwise to press such fragmentary evidence too hard, and we shall content ourselves with the broad conclusion that so far as these eight types of equipment are representative the rise of repair costs with age—in terms of *average* experience, of course—appears to proceed at a rate which, though by no means constant, is not too far from it.

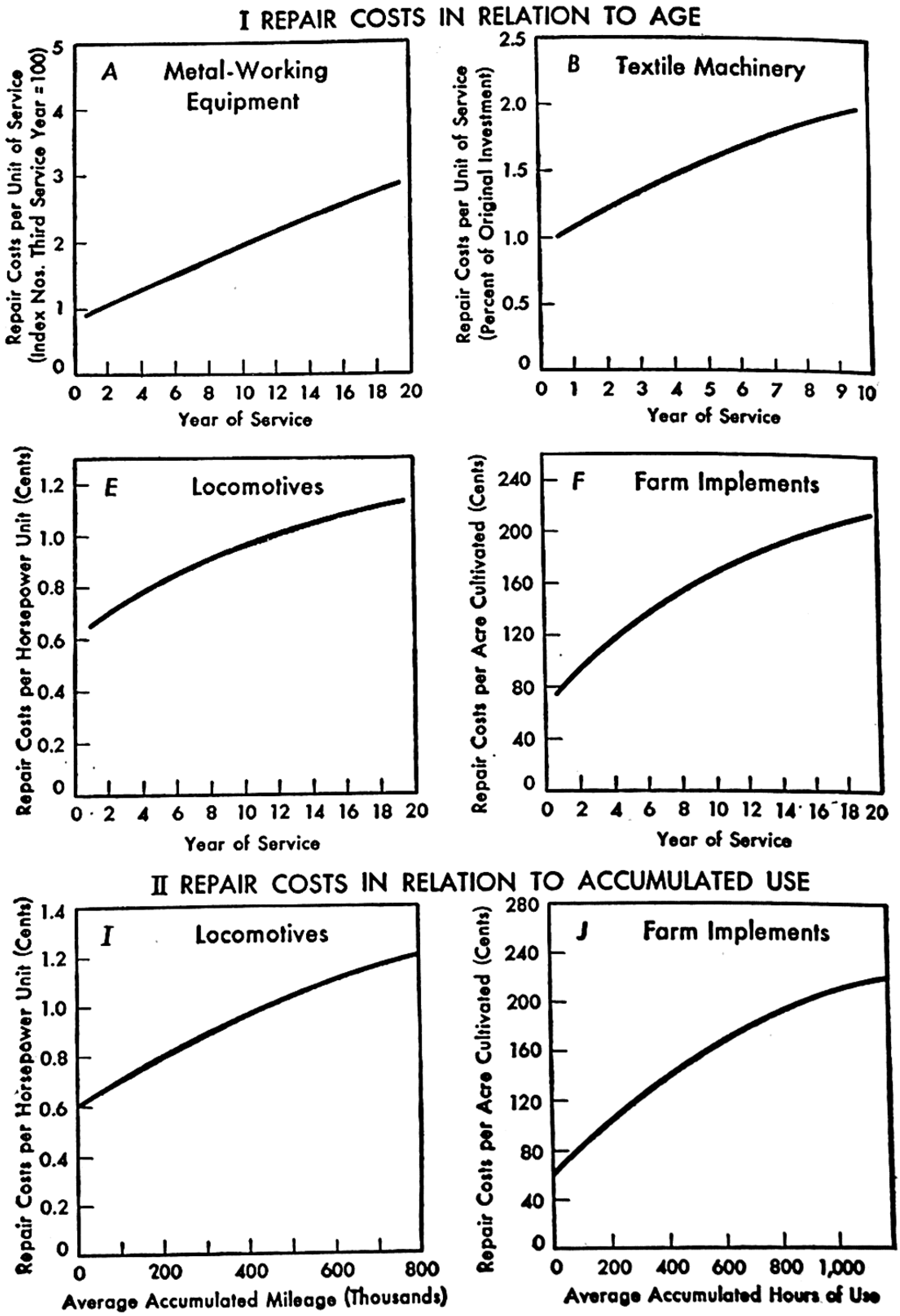
While maintenance is probably the most important age-related operating cost in the majority of cases, there are others. The cost of spoiled work may go up with loss of precision. There may be an increase in the cost of shutdowns and inter-

[1] This is in line with the theoretical expectation. For it is obvious that these costs cannot continue *indefinitely* to rise at a constant rate, whether the original rate or any other. Even if the line rises at a constant rate in the earlier years of service, there must be a point beyond which the annual increment tapers off, else the yearly repair bill will eventually exceed the entire cost of the unit concerned. There is reason to believe that for most types of equipment this point occurs fairly early.

[2] A close inspection will disclose that the curvature is slightly less when repairs are related to accumulated use. It is possible to argue that because of certain characteristics of the available data this milder curvature better represents what the relation of repair costs to age should be for our purpose than do the figures shown in Part I of the chart, but this is too fine a point to raise in connection with calculations as crude as these necessarily are. For those interested in such niceties, the argument is briefed on p. 251.

CHART 2

RELATION BETWEEN AGE OR ACCUMULATED

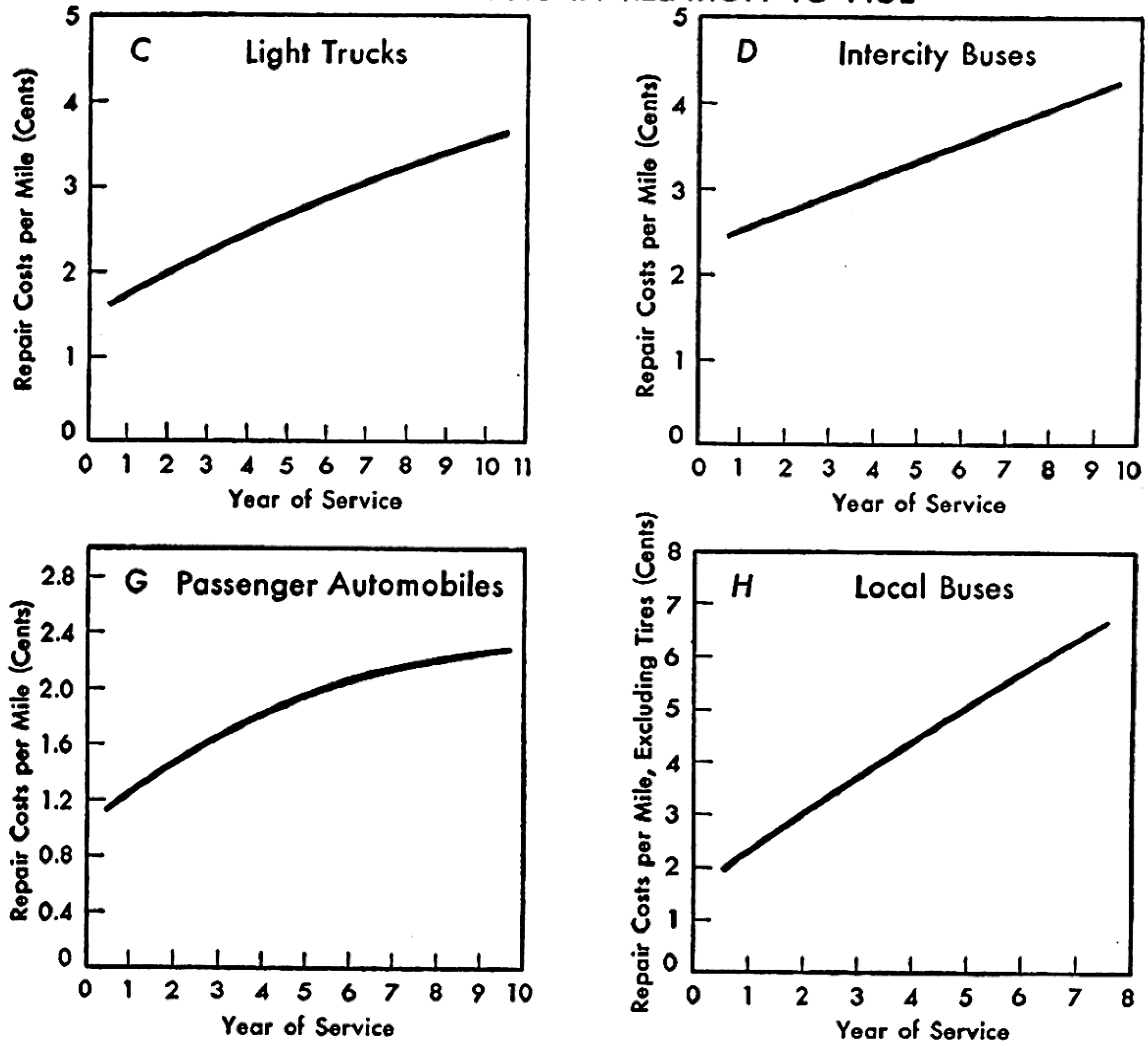


[a] For sources and methods, see p. 247.

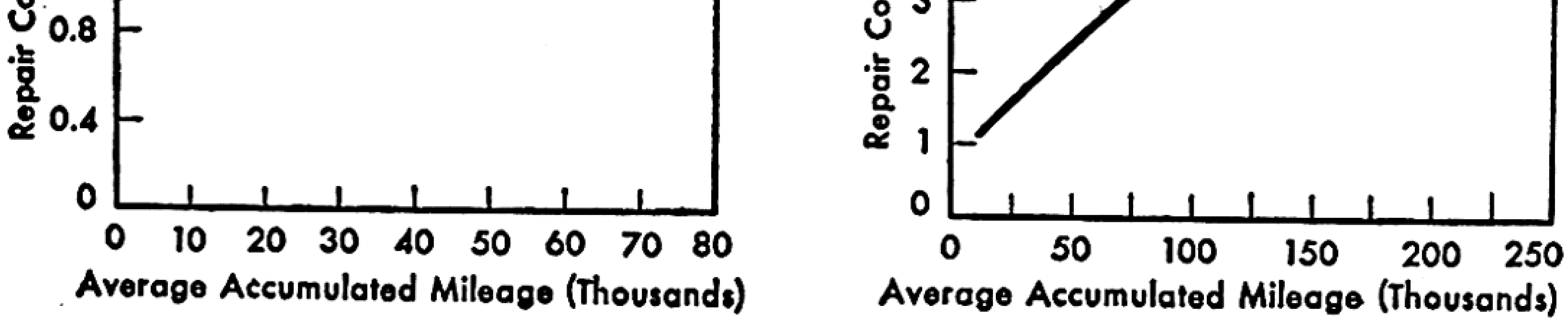
CHART 2 (*Continued*)

USE AND REPAIR COST PER UNIT OF SERVICE[a]

I REPAIR COSTS IN RELATION TO AGE



II REPAIR COSTS IN RELATION TO ACCUMULATED USE



ruptions of production due to mechanical failures. And so on. But on these contributors to deterioration no statistics are available. It has been suggested that if repair costs tend to rise faster in the early years of service than later, these other costs tend to rise slowly at first and then more rapidly, hence that the combination of all must have, in general, a more nearly constant rate of increase than any one taken alone—but this is at best an interesting speculation.

Even if it could be shown that deterioration proceeds at a substantially constant rate in terms of an average for all types of productive equipment, this would not necessarily be true of the average for any particular type, much less for a particular type in a particular service. Many kinds of equipment, for example, have a more or less predictable rhythm or cycle of maintenance, with alternating light and heavy repairs. In some cases other age-related costs have a fairly definite time pattern. Obviously no standard assumption can provide more than a presumptively reasonable projection of the average experience of equipment in general.

OBSOLESCENCE AND DETERIORATION COMBINED

It will be evident from the foregoing discussion that the assumption of a constant accumulation of obsolescence, being grounded on the theory of probability, is more solid than the corresponding assumption as to deterioration, which rests, as we have seen, on fragmentary and inadequate empirical evidence. Since obsolescence and deterioration combine to yield inferiority, it follows that our basic assumption of a constant rate of accumulation for the latter is the more solid in proportion as obsolescence is a larger factor in the total. For any errors in the assumption of constancy as applied to deterioration are damped in the total by the correctness of this assumption as applied to obsolescence. Since the latter is probably the major element in the inferiority accumulation of most types of equipment, this damping effect is very significant.

While it may affect somewhat the general validity of the

assumption of constant inferiority accumulation, the relative importance of obsolescence and deterioration makes no difference to the application of that assumption in a replacement formula. As we shall see shortly, the significant factor from that standpoint is the growth of the *total* operational gap between a machine and its best alternatives, not the division of that gap into components. As a standard projection for this total gap, the assumption of constant accumulation is not only supremely simple—an advantage that will be apparent later—but on the basis of our limited knowledge it appears otherwise the best available.

CONCLUSION

The two standard assumptions developed above are exceedingly simple, as we may realize even more clearly when they are restated together:

1. Future challengers will repeat the adverse minimum of the present one.
2. The present challenger will accumulate operating inferiority at a constant rate.

Whatever may be said of these assumptions, they are clear and definite. In using them—or rather, the replacement formula they yield—the analyst knows exactly where he stands. If he thinks the assumptions inapplicable in some respects to the case in hand, he can modify the results of the formula as his judgment indicates, but he has at least a bench mark or point of departure to work from. We shall have something to say later on about the circumstances which justify such adjustments, but before we can do that we must first develop the replacement formula (together with its practical short cuts) which results from the application of the assumptions as stated.

Chapter VI

THE ASSUMPTIONS APPLIED

Having now laid down two standard assumptions, we are in a position to develop a method or formula for replacement analysis in harmony with them. This is the task of the present chapter.

While these assumptions accomplish a vast and indispensable simplification of our analytical problem, as we shall see, the replacement formula they yield is still not simple enough for convenient practical application, hence we shall undertake in the next chapter to develop an approximately equivalent shortcut. In the meantime, however, we must remain in the intellectual stratosphere. For it is only when we have attained a clear understanding of the theoretical formula itself that we can proceed to its final simplification.

NATURE OF THE PROBLEM

In our preliminary discussion of the nature of the replacement problem (page 50), we pointed out that the consequences of reequipment decisions ordinarily run far beyond the lives of the existing machines under comparison (challenger and defender) and that the real choice is between the best mechanical successions headed by these machines. If it is true, as we have said more recently, that the proper object of equipment policy is to minimize the time-adjusted average of capital cost and operating inferiority, *the function of a replacement formula must be to determine whether the best mechanical succession headed by the present challenger yields a lower average of these magnitudes than the best succession headed by the defender.*

Since we are dealing with mechanical *successions* on both sides, composed, for the most part, of machines not yet in

existence, the capital cost and operating inferiority of which are therefore unpredictable, the first step in the development of such a formula must be to dispose of these future machines by assumption, so that the replacement analysis can be made from data and estimates for existing machines only. This, we have seen, is the purpose of our first standard assumption. By fixing the relation of future challengers to the present one (they will have the same adverse minimum), it makes possible their exclusion from direct or explicit consideration and rests the analysis on the two machines which head the successions, the defender and the current challenger. We need no longer deal with these mechanical ghosts of the future.

THE TECHNIQUE OF EXORCISM

Let us take a closer look at the device by which these ghosts are exorcised, considering first the mechanical succession headed by the present challenger.

Since by assumption all future challengers will have the same adverse minimum as the present one, the best succession headed by the latter is necessarily a sequence of machines of like minimum. It is easy to show in this case that the time-adjusted average of capital cost and operating inferiority for the succession as a whole (its "adverse average") is identical with the adverse minimum of any of the machines composing it, including, of course, the present challenger.[1] Thus it is possible under this assumption to derive the adverse average for the entire succession by the analysis of data for the challenger alone.

But how about the best succession headed by the defender? Since by assumption this succession will consist, for the period *after* the defender's replacement, of machines having the same adverse minimum as the present challenger, it will have an adverse average for this period identical with that of the challenger's succession as a whole. This means, obviously, that any difference between the adverse averages of

[1] Assuming, of course, that each machine is kept in service for the period that yields its adverse minimum. For mathematical proof see p. 253.

the two successions must arise in the period *before* the defender's replacement. This difference is determinable by the analysis of data for the defender alone.

We can put the matter otherwise by saying that since by assumption both successions have the same adverse average *after* the replacement of the machines that head them, the question of which succession has the lower average overall, including the lead machine, turns on which lead machine has the lower adverse minimum. *Given this assumption, therefore, replacement analysis becomes simply a comparison of the adverse minima of challenger and defender.*

Obviously it is necessary before we can make such a comparison to develop a procedure for deriving these adverse minima. Suppose we begin with the challenger.

I. Deriving the Challenger's Adverse Minimum

We have just seen that our first standard assumption, by exorcising future machines from the replacement formula, reduces the analysis to the derivation and comparison of the adverse minima of the existing challenger and defender. It remains, before we proceed, to add a further word about our second assumption. As the reader will recall, this states that the challenger will accumulate deterioration and obsolescence (operating inferiority) at a constant rate over its service life.

THE INFERIORITY GRADIENT

For the sake of convenience we propose to coin a term for this constant rate of accumulation. We shall call it "the inferiority gradient" or, more simply, "the gradient." We shall express it, moreover, as a rate *per year*. It is, then, the annual rate at which the operational gap widens between the machine in service and its best current alternative.

In computing the present challenger's adverse minimum, we shall take as par for the measurement of its operating inferiority the *first-year* performance of the best alternative

(the then challenger) available at the time of reference. We shall assume, therefore, that in its first year of service the present challenger, being measured against itself, has *no* inferiority; that in its second year it will be inferior to the then-available challenger by one year's gradient; that in its third year it will be inferior by twice the gradient; and so on. Thus, if the gradient is $100 a year, the third-year inferiority will be $200.

With this explanation, we propose now to compute the adverse minima of three hypothetical challengers, alike as to acquisition cost and inferiority gradient but differing as to two other factors—salvage value and capital additions. We begin with the simplest case.

THE NO-SALVAGE CASE

Here we have a challenger that will carry no salvage value after installation and will require no capital additions after the necessary original investment of $5,000. Its inferiority gradient is $100 a year.[1] The interest rate for the calculation is 10 per cent.[2] The successive steps in the calculation are set forth in Table 1.

This rather formidable tabulation is obviously in need of some explanation. Let us begin with Col. 1. This gives the *width* of the inferiority gap for each successive year of the present challenger's service life, assuming a gradient of $100 a year. In Col. 2, we have the factors for computing the present worths of the operating inferiorities in the first column, these present worths being shown for individual years in Col. 3 and cumulatively in Col. 4. The next column gives "capital recovery factors" for various periods of time, which are applied to the present worths in Col. 4 to yield the uniform annual equivalents, or time-adjusted averages, in Col. 6.

[1] The practical problem of estimating the gradient will be discussed in a later chapter.

[2] Chap. X is devoted entirely to the question of the appropriate interest rate for replacement analysis. Pending that discussion we shall use 10 per cent for illustrative purposes, not with any implication that this is the "correct" rate, but simply because we must use something.

TABLE 1

DERIVATION OF ADVERSE MINIMUM OF A CHALLENGER HAVING A COST OF $5,000 AND AN INFERIORITY GRADIENT OF $100 A YEAR, ASSUMING NO CAPITAL ADDITIONS AND NO SALVAGE VALUE, WITH INTEREST AT 10 PER CENT[a]

Year of service	Operating inferiority for year indicated	Present worth factor for year indicated[b]	Present worth of operating inferiority for year indicated (Col. 1 × Col. 2)	Present worth of operating inferiority for period ending with year indicated (Col. 3 cumulated)	Capital recovery factor for period ending with year indicated[c]	Time-adjusted annual average for period ending with year indicated: Operating inferiority (Col. 4 × Col. 5)	Capital cost ($5000 × Col. 5)	Both combined (Col. 6 + Col. 7)
	1	2	3	4	5	6	7	8
1	$ 0	$.909	$ 0	$ 0	$1.100	$ 0	$5,500	$5,500
2	100	.826	83	83	.576	48	2,881	2,929
3	200	.751	150	233	.402	94	2,011	2,104
4	300	.683	205	438	.315	138	1,577	1,716
5	400	.621	248	686	.264	181	1,319	1,500
6	500	.565	282	968	.230	222	1,148	1,371
7	600	.513	308	1,276	.205	262	1,027	1,289
8	700	.467	327	1,603	.187	300	937	1,238
9	800	.424	339	1,942	.174	337	868	1,205
10	900	.386	347	2,289	.163	373	814	1,186
11	1,000	.351	351	2,640	.154	406	770	1,176
12	1,100	.319	351	2,990	.147	439	734	*1,173
13	1,200	.290	348	3,338	.141	470	704	1,174
14	1,300	.263	342	3,680	.136	500	679	1,178
15	1,400	.239	335	4,015	.131	528	657	1,185
16	1,500	.218	327	4,342	.128	555	639	1,194
17	1,600	.198	317	4,658	.125	581	623	1,204
18	1,700	.180	306	4,964	.122	605	610	1,215
19	1,800	.164	294	5,258	.120	629	598	1,226
20	1,900	.149	283	5,541	.117	651	587	1,238

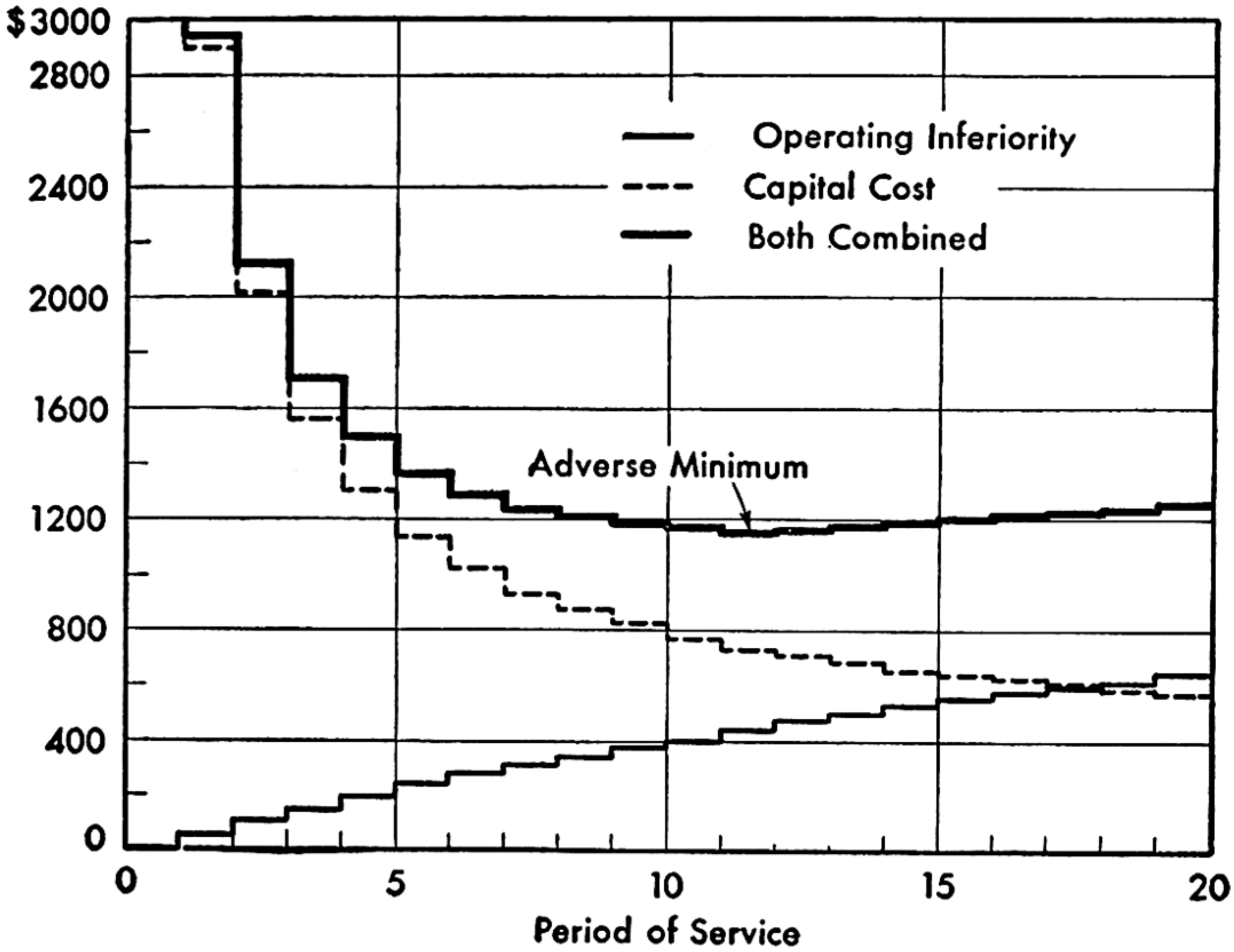
[a] Operating inferiorities treated as year-end magnitudes. Figures do not always add exactly because of rounding.

[b] The factor gives the present worth of $1 payable at the end of the year indicated.

[c] The factor gives the annuity, payable (at the end of each year) over the period indicated, which has a present worth of $1.

CHART 3

GRAPHIC REPRESENTATION OF COLS. 6, 7, AND 8 IN TABLE 1
(Time-adjusted annual average for period ending with year indicated)



These factors are then applied to the present worth of capital cost, $5,000 (which in the absence of salvage values or capital additions is the same for all periods of service) to yield the time-adjusted annual averages in Col. 7. Finally, Col. 8, the pay-off on the calculation, displays the combined sum of the annual averages in the two columns preceding, the lowest obtainable being $1,173 for a 12-year period of service. This $1,173 is the adverse minimum we are seeking.[1]

[1] As indicated a moment ago, the time-adjusted averages in Cols. 6, 7, and 8 are technically known as uniform annual equivalents. We commented briefly on the nature of these equivalents in a previous chapter (footnote, p. 47), pointing out that they differ from ordinary averages. This proposition can be further illustrated from the present table. Thus the cumulative total of operating inferiority for 10 years (Col. 1) is $4,500, yielding a simple average of $450 a year for the period, but the uniform annual equivalent (Col. 6) is $373. Again, the simple annual average of capital cost over 10 years is $775 ($5,000 ÷ 10 plus average interest of $275), but the adjusted figure is $814 (Col. 7).

For those unfamiliar with the matter, we may add that the uniform annual equivalent is obtained by first deriving the present worth (at the prescribed

It may help to clarify the relations between operating inferiority, capital cost, and the sum of the two if we represent them graphically. Chart 3 translates the data in Cols. 6, 7, and 8 into lines *A*, *B*, and *C*, respectively.

The course of series *C*, the combined average of operating inferiority and capital cost, is rapidly downward at first owing to the great saving of annual capital cost, *B*, with increasing periods of service, but the rate of decline tapers, reaching zero at 12 years, and is followed by a slow rise thereafter. The 12-year service life yields the adverse minimum.

THE SALVAGE-VALUE CASE

We simplified the first example by assuming no capital additions and no salvage value. What does the calculation look like when we introduce salvage values? Suppose we take the same challenger described in Table 1 except that we add estimates of salvage value at the end of each year of service. It will not be necessary to show again all the steps outlined in that table, some of which we shall short-circuit here.

We developed in Chap. III (page 39) the proposition that once a machine is installed, the capital cost of keeping it in service for any given year is *the cost of foregoing the opportunity to sell.* This cost equals the loss of salvage value during the year, plus interest on the opening value. In Col. 4 of Table 2 it is shown for successive years in the life or our hypothetical challenger, the components appearing separately in Cols. 2 and 3. Col. 5 gives the year-by-year operating inferiority and Col. 6 the sum of capital cost and inferiority.

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interest rate) of the series to be averaged and then finding the level annuity for the period in question that has the same present worth. Having the same present worth, it is the "equivalent" of the original series. This annuity will amortize its present worth over the period and yield interest on the unamortized balance throughout at the rate prescribed. It is readily computed from tables of "capital recovery factors," to be found in investment manuals or in texts on engineering economy. We have previously suggested Eugene L. Grant, *Principles of Engineering Economy*, rev. ed., Chaps. 4 and 8, and p. 418.

TABLE 2

DERIVATION OF ADVERSE MINIMUM OF A CHALLENGER HAVING A COST OF $5,000, AN INFERIORITY GRADIENT OF $100 A YEAR, AND SALVAGE VALUES AS INDICATED, WITH INTEREST AT 10 PER CENT[a].

Year of service	Salvage value (end of year)	Loss of salvage value during year	Interest on opening salvage value for year indicated	Capital cost for year indicated (Col. 2 + Col. 3)	Operating inferiority for year indicated	Capital cost and operating inferiority for year indicated (Col. 4 + Col. 5)	Time-adjusted annual average for period ending with year indicated: Operating inferiority	Time-adjusted annual average for period ending with year indicated: Capital cost	Time-adjusted annual average for period ending with year indicated: Both combined (Col. 7 + Col. 8)
	1	2	3	4	5	6	7	8	9
1	$4,200	$800	$500	$1,300	$ 0	$1,300	$ 0	$1,300	$1,300
2	3,500	700	420	1,120	100	1,220	48	1,214	1,262
3	2,900	600	350	950	200	1,150	94	1,134	1,228
4	2,400	500	290	790	300	1,090	138	1,060	1,198
5	2,000	400	240	640	400	1 040	181	991	1,172
6	1,700	300	200	500	500	1,000	222	928	1,150
7	1,400	300	170	470	600	1,070	262	880	1,142
8	1,200	200	140	340	700	1,040	300	832	1,133
9	1,000	200	120	320	800	1,120	337	795	1,132*
10	800	200	100	300	900	1,200	373	764	1,137
11	600	200	80	280	1,000	1,280	406	737	1,144
12	500	100	60	160	1,100	1,260	439	710	1,149
13	400	100	50	150	1,200	1,350	470	688	1,158
14	300	100	40	140	1,300	1,440	500	668	1,169
15	200	100	30	130	1,400	1,530	528	651	1,180

[a] Figures do not always add because of rounding.

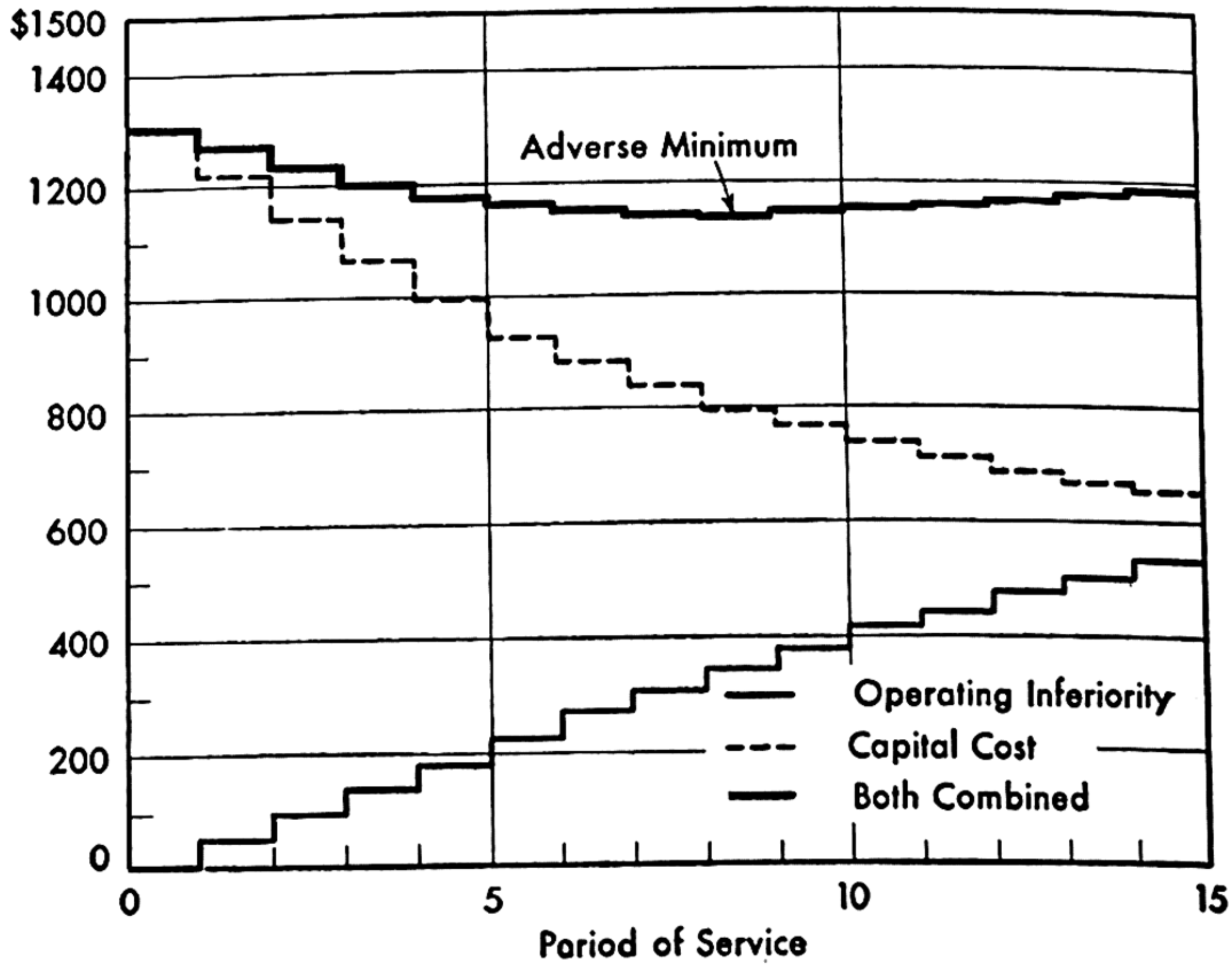
Finally, Cols. 7 to 9 give time-adjusted annual averages for various periods of service.[1]

The introduction of salvage values reduces the challenger's adverse minimum from $1,173 (Table 1) to $1,132 and

CHART 4

GRAPHIC REPRESENTATION OF COLS. 7, 8, AND 9 IN TABLE 2

(Time-adjusted annual average for period ending with year indicated)



shortens from 12 years to 9 the service life which yields the minimum. Both changes depend, of course, on the particular pattern of salvage-value estimates, of which this is only one

[1] The average for capital cost and operating inferiority in Col. 9 may be computed either directly from Col. 6 or by the addition of Cols. 7 and 8. Col. 8 in turn may be computed either from Col. 4 or by a method not shown here which short-circuits both Col. 4 and its components, Cols. 2 and 3. This method takes the uniform annual equivalent, for each period, of the original investment, $5,000, *minus* the present worth of the salvage value at the end of the period. It is easy to prove that the two procedures yield the same result. The more roundabout derivation shown here is easier to understand and has the further advantage that it yields year-by-year figures for capital cost (Col. 4) which can be combined with similar figures for operating inferiority (Col. 5) to give the total of both (Col. 6). We shall have occasion later on to develop the significance of these single-year figures.

among many, but the procedure—our interest at the moment—remains the same in any event.

It may be interesting again to see the series of annual averages in graphic form. Chart 4 translates the figures of Cols. 7, 8, and 9, into lines *A*, *B*, and *C*, respectively.

Here the average for operating inferiority and capital cost combined, line *C*, has a notably different movement than in the no-salvage example, starting much lower and declining therefore less rapidly in the early years. Obviously this reflects the effect of the assumed salvage values in lowering the average annual capital cost for short periods of service. In the absence of salvage, any period, however brief, must absorb the entire cost of the asset, but with salvage the necessary absorption is of course reduced.

THE CASE WITH BOTH SALVAGE VALUES AND CAPITAL ADDITIONS

Having added the complication of salvage values in the preceding example, we may now complete the picture by supposing that the same challenger requires capital additions of $500 every third year, as shown in Table 3.

The inclusion of these periodic capital additions yields an adverse minimum of $1,256 for an 8-year life as against a minimum of $1,173 for a 12-year life with no salvage or $1,132 for a 9-year life with salvage but no additions.[1]

It may be appropriate to remind the reader again that the particular figures employed in these examples are of no consequence. We are simply illustrating the theoretically correct method of deriving the challenger's adverse minimum under our standard assumptions, without regard, for the moment, to practical considerations. As indicated earlier, we shall come down to earth in the next chapter. In the mean-

[1] In using the same salvage values as Table 2, the current example ignores the effect on these values of the periodic capital additions themselves, which might properly be supposed to superimpose a wave motion on the declining trend. We have carried the earlier values forward simply for the sake of continuity and convenience. A more elaborate pattern would in no way alter the procedure of calculation, our only concern at the moment.

TABLE 3

DERIVATION OF ADVERSE MINIMUM OF A CHALLENGER HAVING A COST OF $5,000, AN INFERIORITY GRADIENT OF $100 A YEAR, AND SALVAGE VALUES AS INDICATED, WITH CAPITAL ADDITIONS OF $500 EVERY THIRD YEAR, AND INTEREST AT 10 PER CENT[a]

Year of service	Salvage value (end of year)	Capital cost for year indicated			Operating inferiority for year indicated	Capital cost and operating inferiority for year indicated (Col. 4 + Col. 5)	Time-adjusted annual average of capital cost and operating inferiority for period ending with year indicated
		Loss of salvage plus interest on opening salvage (Col. 4, Table 2)	Capital additions	Total			
	1	2	3	4	5	6	7
1	$4,200	$1,300		$1,300	$ 0	$1,300	$1,300
2	3,500	1,120		1,120	100	1,220	1,262
3	2,900	950	$500	1,450	200	1,650	1,379
4	2,400	790		790	300	1,090	1,317
5	2,000	640		640	400	1,040	1,272
6	1,700	500	500	1,000	500	1,500	1,301
7	1,400	470		470	600	1,070	1,277
8	1,200	340		340	700	1,040	1,256*
9	1,000	320	500	820	800	1,620	1,283
10	800	300		300	900	1,200	1,278
11	600	280		280	1,000	1,280	1,278
12	500	160	500	660	1,100	1,760	1,300
13	400	150		150	1,200	1,350	1,302
14	300	140		140	1,300	1,440	1,307
15	200	130	500	630	1,400	2,030	1,330

[a] Capital additions and operating inferiorities treated as year-end magnitudes. Figures do not always add exactly because of rounding.

time, we have still to derive the adverse minimum for the defender.

II. Deriving the Defender's Adverse Minimum

Having calculated the challenger's adverse minimum under various assumed conditions, it remains to compute the adverse minimum of the defender. This can be done by setting up a table generally similar to the one used for the challenger.

Suppose we have a defender whose next-year operating inferiority *relative to the present challenger* is $1,000.[1] Its inferiority gradient, let us say, is $100 a year. Present salvage value is $1,500, with future values as indicated in the table on the following page:

On this showing, the defender's adverse minimum is $1,504 for 4 years of further service. This does not mean, of course, that the defender should necessarily be kept for 4 more years. Indeed, if the challenger's adverse minimum is below $1,504, it should not be kept at all. It means simply that 4 years is its best period for comparison with the challenger.

THE NEXT-YEAR TEST

While in this example the defender's adverse minimum is for more than one year of further service, in most cases it will not be. If the asset has become an appropriate object for a replacement analysis, its normal, or representative, operating inferiority will usually be rising faster than its capital cost (if any) is falling, giving a rising trend for the two combined. For this reason it can usually be assumed that the next-year total of these factors is the adverse minimum.

This generalization raises practical considerations more appropriate to later chapters than to the present theoretical discussion, and we shall therefore defer its validation accordingly. It cannot be denied, in any event, that there are some

[1] We indicated earlier that the first-year performance of the challenger current at the time is the standard from which the inferiority of an incumbent machine is reckoned. Next year is, of course, the first year for the present challenger, hence its performance is the standard for reckoning next year's defender inferiority.

TABLE 4

DERIVATION OF ADVERSE MINIMUM FOR DEFENDER HAVING NEXT-YEAR OPERATING INFERIORITY OF $1,000 AND A GRADIENT OF $100 A YEAR, WITH SALVAGE VALUES AS INDICATED AND INTEREST AT 10 PER CENT[a]

Year of further service	Salvage value (end of year)	Loss of salvage during year indicated	Interest on opening salvage of year indicated	Capital cost for year indicated (Col. 2 + Col. 3)	Operating inferiority for year indicated	Capital cost and inferiority for year indicated (Col. 4 + Col. 5)	Time-adjusted average of capital cost and inferiority for period ending year indicated
	1	2	3	4	5	6	7
0	$1,500						
1	1,100	$400	$150	$550	$1,000	$1,550	$1,550
2	800	300	110	410	1,100	1,510	1,531
3	600	200	80	280	1,200	1,480	1,516
4	500	100	60	160	1,300	1,460	1,504*
5	400	100	50	150	1,400	1,550	1,511
6	300	100	40	140	1,500	1,640	1,582

[a] Figures do not always add because of rounding.

cases in which the defender's next-year combined inferiority and capital cost may be higher than the average obtainable for a longer period, and in which it is desirable to test alternative periods against next year as we have done in Table 4.[1] We shall merely observe at this point that if the next-year figure for these two magnitudes is treated as the adverse minimum the calculation becomes simple and easy compared with the derivation of the challenger's minimum. It requires no estimates or projections more than a year ahead.

III. The Challenge Itself

The basic problem of replacement analysis we have already stated: Will the best mechanical succession headed by the present challenger have a lower time-adjusted average of capital cost and operating inferiority (adverse average) than the best succession headed by the defender? This problem, utterly hopeless as stated, we have simplified by assuming that future challengers will have the same adverse minimum as the present one. By equating the adverse averages of both successions for the period *following* the tenure of the leading machines (the defender and the present challenger) this assumption reduces the analysis to the derivation and comparison of the adverse minima of these machines alone. For on this basis the succession with the lower adverse average is necessarily the one headed by the machine with the lower adverse minimum.

This means, of course, that when we have derived the adverse minima of challenger and defender we have completed the replacement analysis except for the final step, the comparison of the two minima.[2] That step is the work of a moment. Suppose, for example, that the challenger in question is the

[1] Obviously it is unnecessary to run such a test, even when it is suspected that the defender's adverse minimum is for some period longer than a year, if there is good reason to believe that that minimum, once computed, will still be higher than the challenger's. This point will also be developed later on.

[2] We are not concerned at this stage of the argument with another step that may be involved in practice: shading the challenger's minimum to allow for anticipated deviations from the pattern of developments laid down by the standard assumptions.

TABLE 5

DERIVATION OF ADVERSE MINIMA OF THREE CONTENDERS FOR THE ROLE OF CHALLENGER, *A*, *B* AND *C*, HAVING A LIKE INFERIORITY GRADIENT OF $100 A YEAR AND COSTING $5,000, $3,000, AND $2,500, RESPECTIVELY; *B* AND *C* SHOWING A CURRENT (NEXT-YEAR) OPERATING INFERIORITY OF $300 AND $500, RESPECTIVELY, RELATIVE TO *A*. (ASSUMING NO SALVAGE VALUES OR CAPITAL ADDITIONS, INTEREST AT 10 PER CENT)[a]

Year of service	Operating inferiority for year indicated			Time-adjusted annual average for period ending with year indicated								
				Operating inferiority			Capital cost			Both combined		
	A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
1	$ 0	$ 300	$ 500	$ 0	$300	$ 500	$5,500	$3,300	$2,750	$5,500	$3,600	$3,250
2	100	400	600	48	348	548	2,881	1,729	1,441	2,929	2,076	1,989
3	200	500	700	94	394	594	2,011	1,206	1,005	2,104	1,600	1,599
4	300	600	800	138	438	638	1,577	946	789	1,716	1,385	1,427
5	400	700	900	181	481	681	1,319	791	660	1,500	1,272	1,341
6	500	800	1,000	222	522	722	1,148	689	574	1,371	1,211	1,296
7	600	900	1,100	262	562	762	1,027	616	513	1,289	1,179	1,275
8	700	1,000	1,200	300	600	800	937	562	469	1,238	1,163	1,269*
9	800	1,100	1,300	337	637	837	868	521	434	1,205	1,158*	1,271
10	900	1,200	1,400	373	673	873	814	488	407	1,186	1,161	1,280
11	1,000	1,300	1,500	406	706	906	770	462	385	1,176	1,168	1,291
12	1,100	1,400	1,600	439	739	939	734	440	367	1,173*	1,179	1,306
13	1,200	1,500	1,700	470	770	970	704	422	352	1,174	1,192	1,322
14	1,300	1,600	1,800	500	800	1,000	679	407	339	1,178	1,207	1,339
15	1,400	1,700	1,900	528	828	1,028	657	394	329	1,185	1,222	1,357

[a] Figures do not always add because of rounding.

one shown in Table 2, while the defender is the specimen in Table 4. The former has an adverse minimum of $1,132, the latter, of $1,504. Replacement is signaled decisively, by a margin of $372 a year.

IV. Picking the Challenger

The reader may have sensed by now a missing link in the analysis. We have defined the "challenger" as the best machine available for the defender's job, but we have not indicated how it can be identified. The discussion presupposes that the challenger is either self-evident or has somehow been selected through an off-stage elimination contest prior to the challenge itself. The best candidate for the defender's job is not always self-evident, of course, and the problem arises how to identify the challenger when there are several contenders for the role.

Suppose we have three apparently eligible machines, *A*, *B*, and *C*. Not knowing in advance which is the best, we take one of them provisionally and test the others against it. As a rule it is convenient to take the one with the best current (next-year) operating performance. This performance then becomes the standard from which the next-year operating inferiority of the others is measured.

To illustrate, let us assume, as in Table 5 opposite that contender *A* has the best next-year performance and that *B* and *C* are inferior in this regard by $300 and $500 respectively. Let us assume further that *A* costs $5,000 against $3,000 for *B* and $2,500 for *C* and, for simplicity, that the inferiority gradient is $100 a year for all three and that we have no salvage value or future capital additions to reckon with.

This analysis finds the three candidates for challenger fairly evenly matched, but with *B* holding the advantage, its adverse minimum being $1,158 against $1,173 for *A* and $1,269 for *C*. It therefore wins the right to challenge the defender.[1]

[1] Since *B* turns out to be the challenger, it may seem that we were in error in taking *A*'s performance provisionally as the base from which to measure the

While the various eligibles for challenger can be sifted in this fashion prior to the challenge itself, it is possible to combine the operation with the challenge simply by adding the defender to the comparison in Table 5. The only requirement is that its next-year operating inferiority be measured, with the others, from the performance of machine *A*, the standard chosen for the test. If its adverse minimum on this reckoning is below the $1,158 shown by *B*, its defense is successful; if not, *B* wins both the contest for the right to challenge and the challenge as well.[1]

current (next-year) inferiority of all three contenders. This is not the case, however, since it can easily be shown that the *differences* between the adverse minima are the same when we use *B*'s performance as the base, or *C*'s for that matter. It is the differences, obviously, that we are interested in. Consider the following.

Machine whose performance is used as base for reckoning next-year inferiority	Resulting adverse minimum of		
	A	*B*	*C*
A	$1,173	$1,158	$1,269
B	873	858	969
C	673	658	769

Clearly, *B* comes out the winner, and by the same margin of advantage, regardless of which performance is chosen as the basis of comparison. (This assumes, of course, that the estimated inferiority gradients are unaffected by the choice.)

[1] It should be noted that when the challenge is conducted as a separate operation, the adverse minimum developed by the challenger in the prior elimination contest may need adjustment before comparison with the defender's minimum. This is the case when the performance of some machine other than the one found to be the challenger is selected provisionally for the purpose of this elimination contest as the standard for the measurement of next-year operating inferiority. For when the defender's next-year inferiority is measured relative to the performance of the challenger—as it ordinarily is when the latter is preselected—the challenger's own next-year inferiority must be similarly measured, that is to say it must be zero, after the model of Tables 1, 2, and 3, above. This means that the adverse minimum derived in the elimination contest must be adjusted to the figure that would have been obtained had the challenger been selected in the first place as the standard of measurement for that contest. This adjustment, fortunately, is simplicity itself. It is necessary only to subtract from the challenger's adverse minimum, as derived, the amount by which its next-year performance falls short of the performance of the machine taken as the provisional standard. In the Table 5 case, this involves the subtraction of $300 from $1,158, leaving $858 as the adverse minimum for the purpose of an independent challenge.

V. Generality of the Procedure

There is one point that we may not have emphasized sufficiently in the foregoing discussion. This method of analysis is not confined, as our illustrations may seem to suggest, to replacements involving one machine at a time. It is equally applicable to the replacement of a group of machines by another group, or of an entire complex of facilities by another complex.

Whatever the nature of the facilities up for replacement analysis, the basic question is the same: Is their lowest combined time-adjusted annual average of capital cost and operating inferiority below or above the corresponding average obtainable from the best alternative? To put it in other terms, now familiar, is their adverse minimum below or above the adverse minimum of the challenging facilities? Since the problem is the same, so also is the solution. It is appropriate to remind the reader, therefore, that if we continue to illustrate the solution by single-machine comparisons, we shall do so, as heretofore, for reasons of convenience and simplicity only. The application is general.

With this long theoretical preparation we are now ready to descend from the clouds and to develop the practical short cuts and expedients in harmony with the theory that must be the ultimate pay-off on the whole investigation. This descent is scheduled to begin in the next chapter.

Chapter VII

SHORT CUTS TO THE CHALLENGER'S ADVERSE MINIMUM

In the lengthy and rather formidable tables of the preceding chapter we presented for a hypothetical challenger a computation of the time-adjusted annual average of operating inferiority and capital cost for each of a series of possible service lives. From the resulting array of life-averages, we then selected the lowest by inspection. This derivation of the adverse minimum is of course much too cumbersome and time-consuming for practical use, its real value being as a foundation for short-cut procedures in harmony with it. It is now time to develop such procedures.

It should be said at the outset that while we are now on our way down from the intellectual stratosphere where we have dwelt so long, our descent in the present chapter will be very gradual. We must leave for later discussion most of the practical problems incident to the short-cut procedures to be presented here, simply assuming the answers in the meantime. Among these problems are the estimation of the challenger's inferiority gradient, the selection of an interest rate for the analysis, and the projection of salvage values and capital additions (if any) over the challenger's service life. All these except the question of the interest rate will engage our attention in the next chapter. For the present we are concerned primarily with the form and character of the available short cuts rather than with their practical application.

If we defer so many problems incident to the application of the short cuts, it will come as no surprise that we defer

also the problem of how to shade the *results* of an application to allow for differences between the pattern of developments premised by our standard assumptions and the pattern anticipated by the analyst. For we must remember that the short cuts, like the more elaborate procedures they abbreviate, rest squarely on these assumptions, hence yield a solution subject to modification whenever the latter are adjudged in some degree inappropriate. It may be proper to repeat that what we are doing, essentially, is setting up a model for use as a guide or bench mark in replacement analysis, to be employed, like any other model, with judgment and discrimination. We are not proposing a universal formula to be applied by rote.

GENERAL PRINCIPLE OF THE SHORT CUTS

The ideal short cut to the challenger's adverse minimum would be a simple formula yielding this minimum directly, exactly, and in one calculation. Unfortunately, there is no such formula. It is impossible to obtain the uniform annual equivalent of operating inferiority for a given period of service without a cumulative calculation covering intervening years. This precludes a direct (noncumulative) derivation of the uniform annual equivalent of inferiority and capital cost combined, including, of course, the lowest annual equivalent obtainable, the adverse minimum.

While there is no *exact* formula that avoids cumulative calculations, we can approximate the desired results noncumulatively (assuming, as we do, a constant inferiority gradient) by substituting simple averages of operating inferiority and capital cost for the uniform annual equivalents theoretically prescribed. We pointed out earlier (page 79) that the simple average of the challenger's inferiority for any period is *higher* than the time-adjusted average, or uniform annual equivalent, while the simple average of its capital cost is *lower* than its adjusted counterpart. This suggests the possibility that these opposite errors may be substantially compensatory, hence that the *sum* of the simple

averages may be not far different from the sum of the uniform annual equivalents. This is in fact the principle on which our short cut rests. By using simple averages we can approximate the challenger's adverse minimum to a very satisfactory degree of accuracy, and with only a fraction of the effort required for a theoretically correct determination.

The procedure is as follows: In lieu of the uniform annual equivalent of operating inferiority, we take the simple average, which is easily computed, under the assumption of a constant gradient, as one-half the product of the gradient times the number of years in the period less one.[1] In lieu of the uniform annual equivalent of capital cost, we take average depreciation plus interest on the average of the purchase price and the salvage value.[2] The sum of the two gives the approximation desired. We can express this operation in the form of an equation.

$$\text{Life-average of operating inferiority and capital cost} = \frac{g(n-1)}{2} + \frac{c-s}{n} + \frac{i(c+s)}{2}$$

when g is the annual inferiority gradient, c the acquisition cost, s the terminal salvage value, n the number of years in the period of service, and i the rate of interest (in decimals).[3]

It will be noted that this expression, which we may call the "general" formula, does not yield the challenger's adverse minimum as such, but merely the life-average of inferiority and capital cost *for the particular service life stipulated.* To get

[1] Since the first year shows zero inferiority, the average inferiority for any period is one-half the product of the gradient times one less than the number of years in the period.

[2] This reckoning obviously takes no account of capital additions, if any, during the service life. The problem of additions will be considered later (p. 103); in the meantime we shall assume that they are either absent or are of such small consequence that they can properly be ignored.

[3] When we are using annual data, as here, the average investment yielded by level, or straight-line, depreciation does not coincide exactly with the last term of the formula, $\frac{c+s}{2}$. To be precise, it is $\frac{c-s}{2}\left(\frac{n+1}{n}\right) + s$. The first expression is easier to compute, however, and is otherwise superior for our purpose.

the adverse minimum with this expression, it is necessary first to arrive somehow at the service life associated with it.

Obviously it is desirable, if possible, to find a formula that will go directly to the adverse minimum without prior determination of the service life. There is such a formula, derivable from the equation just given, that is good whenever the challenger's future salvage values can be ignored. We shall call it, therefore, the "no-salvage" formula. Since it provides a satisfactory approximation to the adverse minimum in the overwhelming majority of cases and is, therefore, our primary or basic short cut, it deserves the first consideration.

I. The No-salvage Case

When the challenger's adverse minimum is unaffected by future salvage values, it is completely determined by three factors: (1) the acquisition cost, (2) the inferiority gradient, and (3) the interest rate. It is possible in this case to obtain a formula for the minimum based on these three factors only. This "no-salvage" formula is as follows:

$$\text{Adverse minimum} = \sqrt{2cg} + \frac{ic - g}{2}$$

when c is, as before, the cost, g the gradient, and i the interest rate (in decimals).[1]

Here is a simple and ready short cut for the no-salvage case. The acquisition cost being known and the interest rate stipulated, the analyst has only one factor to estimate: the inferiority gradient.[2] Not only is the formula exceedingly

[1] For the derivation, see p. 254.

[2] As indicated above, the formula eliminates the need for any estimate of the challenger's service life. In the absence of salvage values, the service life is determined (at any given interest rate) by the relation between the cost of the asset and its inferiority gradient. The estimate of the gradient is sufficient therefore to fix the period of service absolutely. If the analyst is curious about the period, he can derive it (subject only to formula errors) by dividing the gradient into the adverse minimum as provided by the short cut. (The validity of this procedure is supported on p. 255.) If he wishes to obtain it without first deriving the adverse minimum, he can do so by the formula:

$$\text{Service life} = \sqrt{\frac{2c}{g}} + \frac{ic - g}{2g}$$

There appears no real advantage in the latter procedure, however.

simple; it approximates the correct adverse minimum so closely that the deviations are negligible (less than 3 per cent in ordinary cases).[1]

EXAMPLE

Suppose we apply the formula to the challenger in Table 1 (page 78). We then have

$$\begin{aligned}\text{Adverse minimum} &= \sqrt{2 \times 5{,}000 \times 100} + \frac{.10(5{,}000) - 100}{2}\\ &= \sqrt{1{,}000{,}000} + 200\\ &= 1{,}000 + 200 = 1{,}200\end{aligned}$$

Here we obtain an adverse minimum of $1,200, as against the theoretically exact figure of $1,173 in Table 1.

GRAPHIC SHORT CUT FOR THE NO-SALVAGE CASE

For those who prefer it, there is an easy graphic short cut to the challenger's adverse minimum for the no-salvage case. The graphic method takes advantage of the fact that in this case the ratio of the adverse minimum to the acquisition cost is determined, at any given rate of interest, by the ratio of the inferiority gradient to that cost. For this reason it is possible to plot on a diagram the ratios of adverse minimum to cost yielded by various gradient/cost ratios and interest rates. Once the analyst has determined the acquisition cost and has estimated the inferiority gradient, he has only to figure the ratio of the latter to the former and read from the diagram the corresponding ratio of the adverse minimum to the cost. From this the adverse minimum itself is at once available. The procedure may be illustrated by reference to the chart on the opposite page.

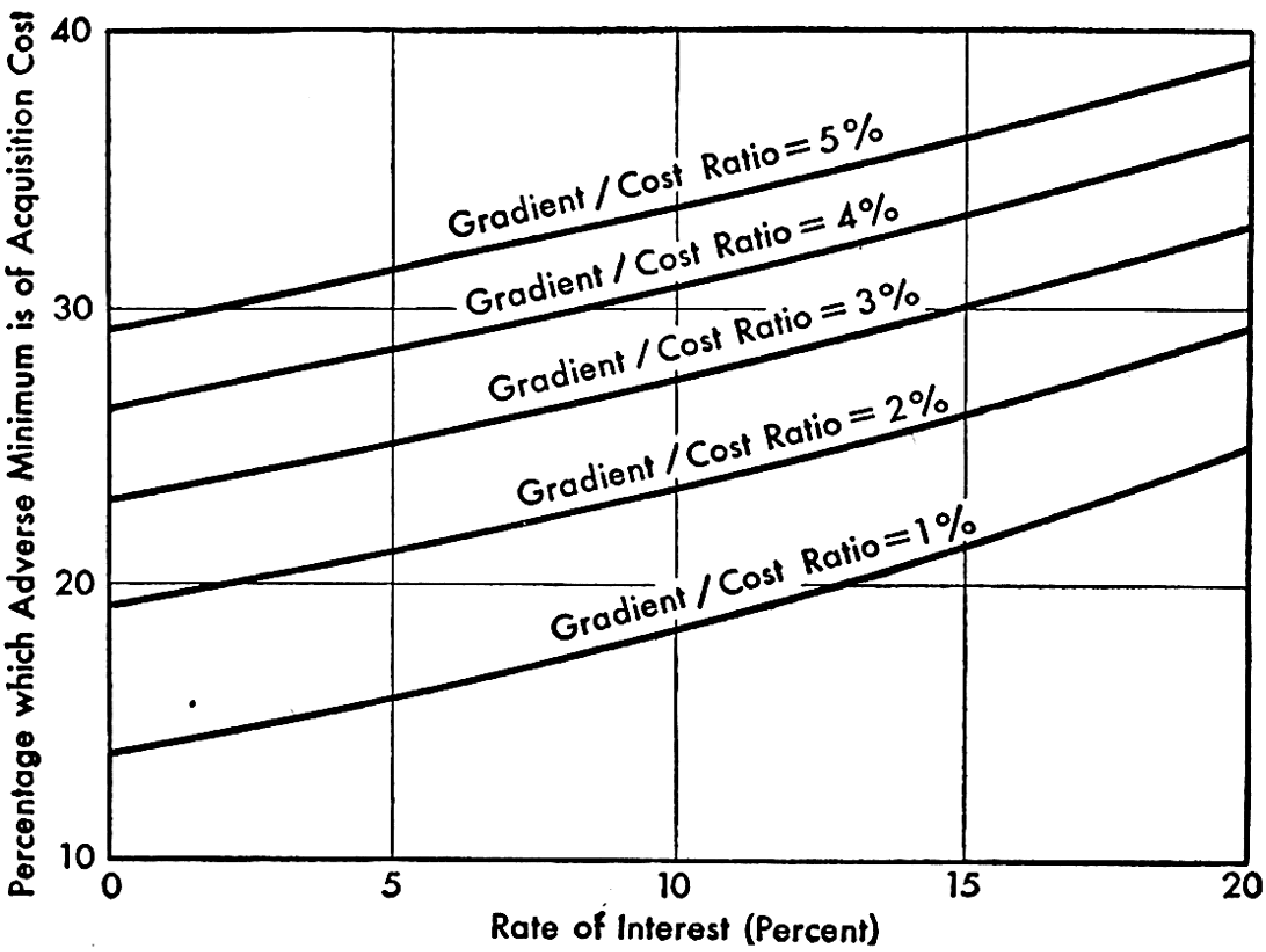
Given the interest rate and the ratio (percentage) of the inferiority gradient to the acquisition cost, we can read off at once on the vertical scale the percentage which the adverse minimum is of this cost (interpolating for ratios between those shown). Suppose, for example, the gradient/cost ratio turns out to be 2.4 per cent. Assuming a 10 per cent interest rate,

[1] For a test of its accuracy, see p. 255.

we run out on the horizontal axis to the 10 per cent line, ascending to a point two-fifths of the way between the lines for the 2 per cent and 3 per cent ratios. Reading the result from the vertical axis, we have approximately 25 per cent as the ratio of the adverse minimum to the cost. Thus if the cost is $10,000, the adverse minimum is $2,500.

CHART 5

CHALLENGER'S ADVERSE MINIMUM AS A PERCENTAGE OF ITS ACQUISITION COST, FOR VARIOUS GRADIENT/COST RATIOS AND RATES OF INTEREST, ASSUMING NO SALVAGE VALUE



It is obvious that given the necessary chart this short cut is exceedingly easy to apply. If the formula for computing the adverse minimum directly were complex and tedious, the graphic approach would have much to commend it, but since on the contrary this formula is exceedingly simple, the alternative has in our opinion no significant advantage. We offer it, however, to those for whom square roots are a bugaboo.[1]

[1] The formula, it will be recalled, is

$$\text{Adverse minimum} = \sqrt{2cg} + \frac{ic - g}{2}$$

II. The Salvage-value Case

It may be inferred from the foregoing discussion that the short-cut formula appropriate to the no-salvage case is inapplicable when the challenger has prospective salvage value. This is not necessarily so, however. The anticipated values may be too low to have an effect on the adverse minimum, or their effect, when present, may be negligible. In either case it is possible to use the adverse minimum derived by the no-salvage formula. Let us consider these possibilities in order.

INEFFECTIVE SALVAGE VALUES

We have just observed that salvage values may be too low to have any effect on the challenger's adverse minimum. From this it may be inferred that there is in every case a line or

Table 6

Hypothetical Challenger of Table 2, with Salvage Values Modified to Yield a Constant Life-average of Operating Inferiority and Capital Cost-over the No-salvage Service Life[a]

Year	Operating inferiority	Salvage value (end of year)[b]	Time-adjusted annual average for period ending with year indicated		
			Operating inferiority	Capital cost	Both combined
	1	2	3	4	5
1	$ 0	$4,327	$ 0	$1,173	$1,173
2	100	3,687	48	1,125	1,173
3	200	3,083	94	1,079	1,173
4	300	2,519	138	1,035	1,173
5	400	1,999	181	992	1,173
6	500	1,526	222	950	1,173
7	600	1,106	263	911	1,173
8	700	744	300	872	1,173
9	800	446	337	835	1,173
10	900	218	373	800	1,173
11	1,000	66	406	766	1,173
12	1,100	0	439	734	1,173

[a] Figures do not always add exactly because of rounding.
[b] Derivation of the figures on p. 256.

course of values below which salvage is ineffective and above which it is effective. The inference is correct.

We can exemplify this "line of indifference," by reference to the challenger described in Table 2 (page 81). A slight modification of the assumed salvage values gives us the results in Table 6, opposite.

Here is a pattern of salvage values that yields the same adverse minimum as the no-salvage case, $1,173, and yields it for any period of service up to 12 years, the no-salvage service life. It describes therefore the line of indifference. Any course of values that lies wholly below this line is ineffective; that is to say, the adverse minimum is the same as if these values were zero. It follows, obviously, that given such a course of values, the adverse minimum can be derived by the no-salvage formula.

SALVAGE VALUES EFFECTIVE BUT NEGLIGIBLE

Since the short cut applicable to the no-salvage case is so much more simple and direct than the procedure required when salvage values are taken into account (as we shall see shortly), the analyst should employ this short cut whenever it promises to yield tolerably satisfactory results.

We suggested earlier that the challenger's salvage values, even though effective, may make so little difference to the adverse minimum that they can properly be disregarded. We have a good example of this in our Table 2 challenger (page 81) whose adverse minimum computed with salvage values is $1,132, against $1,173 without such values (Table 1, page 78). This is a difference of only $41, or 3.6 per cent. In an operation as rough and ready as replacement analysis must necessarily be, an error of this magnitude is of no consequence whatever.

Even an error much larger than this may still be of no consequence. For if replacement is signaled anyway when the challenger's adverse minimum is derived by the no-salvage formula, it may be immaterial that it would be signaled even more loudly with the lower minimum obtainable by taking

salvage values into account. Thus if the defender's adverse minimum is \$2,000 and if the application of the no-salvage formula to the challenger yields \$1,500, of what consequence is it that the minimum obtainable by taking account of challenger salvage values may be \$1,200? Replacement is decisively indicated by either figure.

This suggests, rightly, that even with a challenger having the prospect of effective salvage values the first step is to compute the adverse minimum by the no-salvage short cut. If replacement is signaled with this minimum, well and good; if not, and if the effect of salvage values on the reckoning may be decisive, resort can then be had to the general formula, presented earlier:

$$\text{Life average of operating inferiority and capital cost} = \frac{g(n-1)}{2} + \frac{c-s}{n} + \frac{i(c+s)}{2}$$

The latter is a secondary device to be used only when it promises to alter the replacement decision indicated by the no-salvage formula.

HOW TO TEST FOR THE EFFECT OF SALVAGE VALUES

When the analyst has reason to believe, or to suspect, that the adverse minimum reckoned with salvage value is lower than the no-salvage minimum *by a margin vital to the replacement decision*, he can check his hunch by the use of the general formula. As we pointed out earlier, this does not yield the adverse minimum as such, but only the adverse average for the particular service life stipulated, salvage value at the end of that period being supplied.[1] To identify the lowest average (the adverse minimum) exactly, there is nothing for it but to experiment with different service lives until it is located. It is a case of cut and try.[2]

[1] In this case the adverse minimum is no longer determined, as it is in the absence of salvage, simply by the acquisition cost, the gradient, and the interest rate; in fact there can be as many minima for one combination of these factors as there are possible schedules of effective salvage values.

[2] Like the formula for the no-salvage case, this one gives approximate, rather than exact, results. Again the deviations are negligible, however, the adverse minimum being within 4 per cent of the theoretically correct figure in ordinary cases. For tests of its accuracy, see p. 256.

This may seem a formidable undertaking, but fortunately it is not so bad as it sounds. First of all, it is rarely if ever necessary to locate the adverse minimum *exactly;* an approximation will do just as well and requires much less "fishing." If the estimates of future challenger salvage values are reasonably regular and consistent, the adverse life averages in the vicinity of the minimum are likely to be only slightly above it and can be used in its stead.[1] For this reason a spot check for a few scattered service lives will usually suffice and will in any event indicate whether further exploration is justified.

The application of the formula is further simplified by a second consideration. It can readily be shown that if salvage values are not effective during the first 5 years of the challenger's service life they are most unlikely, even if effective later on, to produce an adverse minimum significantly below the no-salvage minimum.[2] This means that the spot check just referred to can be confined to the early years of service. If the test for these years shows salvage values to be ineffective, the no-salvage adverse minimum can be accepted without further ado.[3]

Let us illustrate: We have a challenger costing $10,000, with an estimated inferiority gradient of $250 a year. Assuming 10 per cent interest, its adverse minimum by the no-salvage

[1] The normal effect of salvage values is to flatten the curve described by these life-averages for increasing periods of service, as the reader may observe by comparing line *C* in Charts 3 and 4 (pp. 79 and 82). All errors from failure to identify the adverse minimum exactly are of course on the high side. Since we are trying to approximate a minimum figure, we are in the position of an explorer sounding for the low point in the bottom of a lake: we can make mistakes only in one direction.

[2] This proposition is supported on p. 257.

[3] There is even available a rough test, good for most cases, to decide whether this spot check is worth while. It can be demonstrated that unless the salvage value anticipated at the end of the challenger's no-salvage service life is in excess of 10 per cent of its acquisition cost it is unlikely that the estimated values for intervening years will yield an adverse minimum significantly below the figure yielded by the no-salvage formula. Since the no-salvage service life is readily available, once the adverse minimum has been computed by this formula (by dividing the inferiority gradient into the minimum) it is easy to make this test before exploring the possible effect of salvage values during the first 5 years of service. For a discussion of this test see p. 260.

short cut is \$2,611.[1] Suppose now that with this minimum the challenger cannot displace the defender, or cannot do so decisively enough, and that it is necessary therefore to ascertain whether the minimum obtainable by taking future salvage values into account is low enough to do the trick. To test, we spot-check with the general formula, using service lives of say 1, 3, and 5 years, for which we estimate terminal salvage values of \$8,000, \$5,000, and \$2,500, respectively.

1 Year

$$\frac{250 \times 0}{2} + \frac{10{,}000 - 8{,}000}{1} + \frac{.10(10{,}000 + 8{,}000)}{2} = \$2{,}900$$

3 Years

$$\frac{250 \times 2}{2} + \frac{10{,}000 - 5{,}000}{3} + \frac{.10(10{,}000 + 5{,}000)}{2} = \$2{,}667$$

5 Years

$$\frac{250 \times 4}{2} + \frac{10{,}000 - 2{,}500}{5} + \frac{.10(10{,}000 + 2{,}500)}{2} = \$2{,}625$$

Since the salvage values estimated for these years are clearly ineffective, producing adverse life averages above the no-salvage minimum of \$2,611, we can take the latter for practical purposes as the challenger's best figure. Suppose, however, that the salvage estimates run higher, at \$8,500, \$6,000, and \$5,000. The picture in this case is decidedly different.

1 Year

$$\frac{250 \times 0}{2} + \frac{10{,}000 - 8{,}500}{1} + \frac{.10(10{,}000 + 8{,}500)}{2} = \$2{,}425$$

3 Years

$$\frac{250 \times 2}{2} + \frac{10{,}000 - 6{,}000}{3} + \frac{.10(10{,}000 + 6{,}000)}{2} = \$2{,}383$$

5 Years

$$\frac{250 \times 4}{2} + \frac{10{,}000 - 5{,}000}{5} + \frac{.10(10{,}000 + 5{,}000)}{2} = \$2{,}250$$

[1] $\sqrt{2 \times 10{,}000 \times 250} + \frac{.10(10{,}000) - 250}{2} = 2{,}611$

Here the projected salvage values are effective for all the test years, yielding an adverse average of $2,250 for a 5-year service, considerably below the no-salvage adverse minimum of $2,611. This figure of $2,250 may or may not be the lowest obtainable from the general formula, a question determinable only by further exploration, but it is certainly close to the bottom, and no further sounding is justified unless indeed (which is hard to imagine) the replacement decision turns on whatever small margin of challenger advantage may be developed.[1]

III. The Problem of Capital Additions

We have been dealing thus far with challengers for which capital additions after installation are assumed to be either absent or negligible. When such additions are significant we have still another variable in the calculation of the adverse minimum. There is no separate short cut for this situation, but a satisfactory solution is possible in most cases without much trouble.

Unlike future salvage values, which, if effective, yield an adverse minimum *below* the no-salvage figure, future capital additions yield one that is *higher*. This means that if the challenge is repulsed on the basis of the no-salvage minimum computed, as heretofore, by our basic formula, there is no need to proceed further. It would be repulsed even more

[1] If we are determined to chase down the salvage-value adverse minimum exactly, we can try service lives of 4 and 6 years. With terminal salvage estimates of $5,500 and $4,500, respectively, we get adverse averages of $2,275 and $2,267, indicating that the figure of $2,250 *is* the minimum—indicating also the futility of such perfectionism. (Incidentally, the adverse minimum for this case by the full, or theoretically correct, procedure is $2,269.)

It may be noted that the spot-check method is reliable in proportion as the curve of the life averages of inferiority and capital cost for varying periods of service is smooth and regular. It is so (assuming, as we do here, a constant inferiority gradient) if the estimates of salvage values at different ages are themselves regular and consistent. An erratic pattern of values produces slight humps and dips in the curve of averages and diminishes accordingly the reliability of inferences drawn from separated points on the curve. The analyst forced to project salvage values should be careful, therefore, to see that his estimates are reasonably "in line."

decisively if the prospective capital additions were taken into account. If, on the other hand, the challenge is good by a substantial margin, it may also be unnecessary to proceed further, since it is improbable that this margin would be wiped out by a recalculation of the adverse minimum with capital additions regarded. As we emphasized in discussing future salvage values, the no-salvage minimum can be used without modification *except when the adjustment promises to be vital to the decision.* In the great majority of cases no adjustment is required.

Since effective salvage values lower the adverse minimum as compared with the no-salvage figure, while capital additions raise it, it is obvious that if both are in prospect they may more or less offset each other, thus qualifying the necessity, if such it appears, for taking either into account. It is obvious also that capital additions, like salvage values, have less effect on the adverse minimum the later they come in the challenger's service life. If they do not occur in the first 5 years, they must be very sizable indeed (in relation to the original investment) in order to make any substantial difference in the adverse minimum.

When the analyst is in doubt whether the inclusion of capital additions is vital to his decision, he can run a test after the manner described in the preceding section for salvage values, spot-checking for selected periods of service up to say 5 years or thereabouts. He should remember in this case, however, that when sizable capital additions are required at various points in the challenger's career its adverse minimum is likely to be associated with a period of service ending just before one of these additions. This means that the service lives chosen for the cut and try should terminate with the years preceding those in which additions are anticipated. Having determined these lives and having computed their respective averages of inferiority and capital cost *without regard to additions*, the analyst can then add in each case an allowance for the additions themselves. This allowance can be computed on a rough-and-ready basis by dividing the

number of years in the service life into the total of additions occurring therein.

AN EXAMPLE

Suppose we revert to the imaginary challenger described in the preceding section, the cost being \$10,000, the gradient \$250 a year, and interest 10 per cent. In this case we estimate that capital additions of \$1,500 will be required during the fourth and sixth years of service, hence we select lives of 3 and 5 years for the test, as follows:

3 Years

$$\frac{250 \times 2}{2} + \frac{10{,}000 - 6{,}000}{3} + \frac{.10(10{,}000 + 6{,}000)}{2} = \$2{,}383$$

Average capital additions, $0 \div 3$ . . . . = 0

Total . . . . = \$2,383

5 Years

$$\frac{250 \times 4}{2} + \frac{10{,}000 - 5{,}000}{5} + \frac{.10(10{,}000 + 5{,}000)}{2} = \$2{,}250$$

Average capital additions, $\$1{,}500 \div 5$ . . . . = 300

Total . . . . = \$2,550

With capital additions taken into the reckoning, the best adverse average developed by the spot-check is \$2,383, as against \$2,250 for a similar test (page 102) in the absence of such additions.[1] The difference is obviously too small to be decisive except in the most unusual circumstances and save in such circumstances is therefore not worth the trouble required to identify it.

IV. The Service-life Approach

The question may well be raised why it is necessary to estimate the challenger's inferiority gradient. Why not estimate its service life instead? It may be argued that this is the time-honored practice, thoroughly familiar to equipment engineers, whereas gradient estimating is totally unfamiliar.

[1] The adverse minimum for this case by the theoretically correct procedure is \$2,442 as compared with the approximation of \$2,383 developed here by the short-cut method.

The only purpose of estimating either the challenger's gradient or its service life is to make possible the computation of its adverse minimum. Given the gradient, as we have seen, this minimum is derivable without an estimate of service life, but the reverse is not true. *Not even the correct service life can yield the adverse minimum without a gradient estimate of some kind.*[1]

All a service-life estimate as such can do is to provide a period of years over which to spread the challenger's capital cost. In the absence of a gradient estimate or its equivalent—in the absence therefore of any recognition of future deterioration and obsolescence—it yields only one of the two components of the adverse minimum. The life average of operating inferiority is left out of account. We can illustrate by reference once more to Table 1 (page 78). Suppose the analyst is lucky enough to guess correctly the challenger's service life of 12 years. Knowing the purchase price, $5,000, he can compute the average annual capital cost for that period, $734, but this is not the adverse minimum, which stands at $1,173. Again, even if he guesses correctly the 9-year service life of the Table 2 challenger (page 81), he will come up with a capital cost of $795 a year, against an adverse minimum of $1,132.

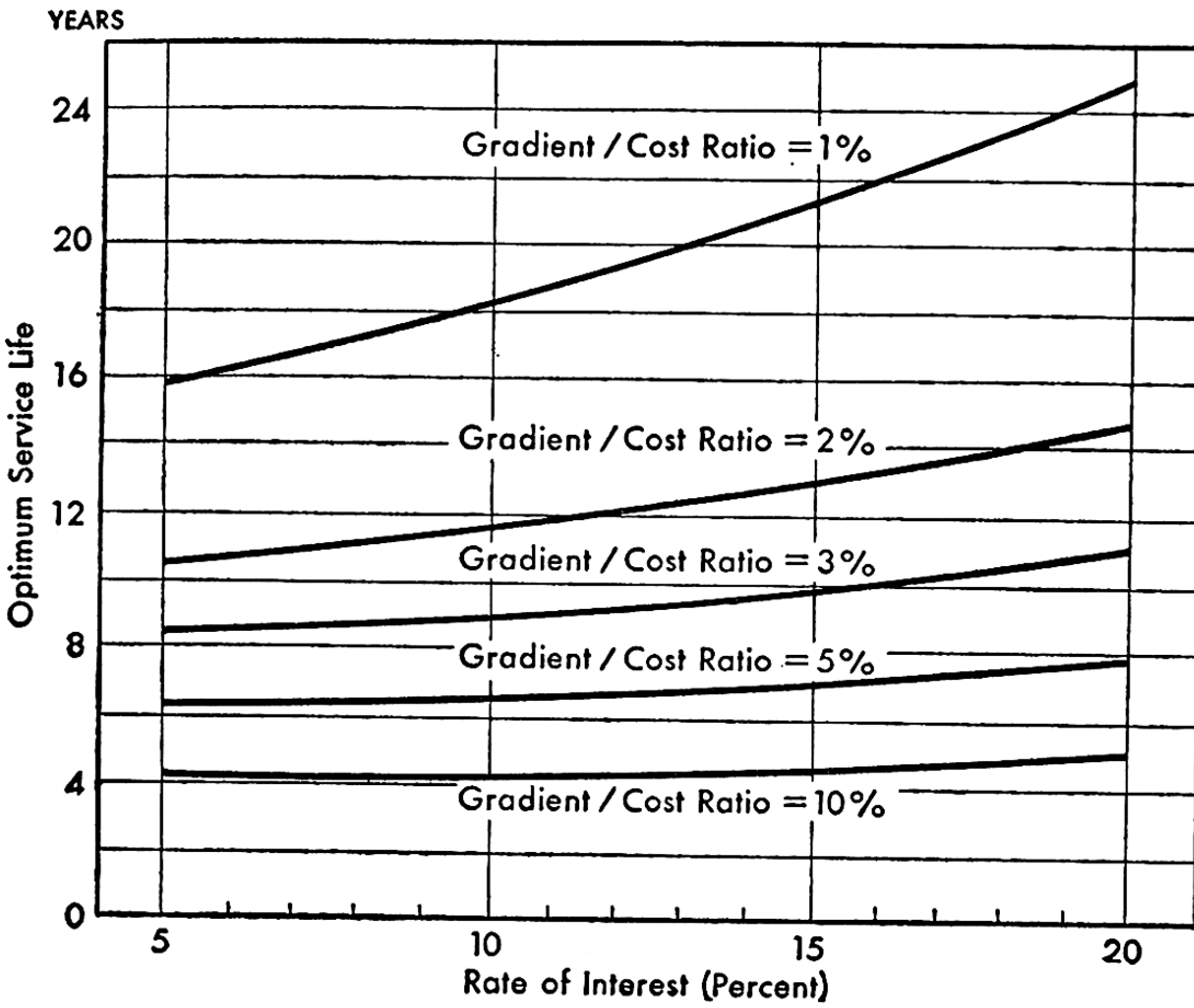
While the adverse minimum is not deducible from a service-life estimate alone, it is possible with our standard assumptions to develop, for the no-salvage case, a procedure by which it can be approximated by the service-life approach. There are in fact two procedures—one graphic, one algebraic. The first is illustrated in Chart 6. This chart shows the correct service life associated with various gradient/cost ratios and interest rates.[2] Conversely, it shows also the gradient/cost ratio associated, at any given interest rate, with different service lives. It is obvious that by specifying a service life and reading from the chart the correlated gradient/cost ratio,

[1] There is one exception to this statement, namely, a challenger subject to neither deterioration nor obsolescence.

[2] We have previously pointed out (p. 95) that in the no-salvage case the service life is determined (at any given interest rate) by the gradient/cost ratio.

CHART 6

CHALLENGER'S CORRECT LIFE, FOR VARIOUS GRADIENT/COST RATIOS AND RATES OF INTEREST, ASSUMING A CONSTANT GRADIENT AND NO SALVAGE VALUE



the analyst can easily derive the gradient for the challenger in hand by applying this ratio to its acquisition cost. He can then solve for the adverse minimum by inserting the gradient thus derived in our regular no-salvage formula:

$$\sqrt{2cg} + \frac{ic - g}{2}.$$

This is, however, a cumbersome and roundabout procedure. Starting with a service-life estimate, the analyst can reach the same end result for the no-salvage case by a simple formula which omits the gradient explicitly but allows for it implicitly:

$$\text{Adverse minimum} = c\left(\frac{2n - 1}{n^2} + \frac{i}{1.4}\right)$$

when c is the acquisition cost, i the interest rate (in decimals), and n the number of years estimated for the economic service life. This will yield approximately the adverse minimum obtained by our regular formula *when the gradient estimate used in the latter yields a service life equal to n.*[1] In other words, by applying this formula to a given estimate of the challenger's service life the analyst will get approximately the same result he would get if he estimated a gradient that yields that same life.[2]

While this formula thus permits us to start with a service-life estimate in the no-salvage case and to obtain substantially the adverse minimum we would get from the correlative gradient projection, it must be remembered that when we estimate the service life rather than the gradient we are estimating the effect rather than the cause. It is the accumulation of deterioration and obsolescence that determines this life, not the reverse. It follows, in strict logic, that when we have no basis for projecting the rate of inferiority accumulation we have likewise no basis for a service-life estimate. If we are blind as to the first, we are necessarily blind as to both.

Even when life estimates are applied to the formula just given, and even when, therefore, they yield an adverse minimum that takes future deterioration and obsolescence into account, the service-life approach has certain disadvantages. For one thing, it lends itself to the use of conventionalized and purely arbitrary "capital recovery periods," applied without any serious effort to appraise the probable tenure of the

[1] The derivation of the formula, and its accuracy, are discussed on p. 261. Since we demonstrated earlier (p. 101) that if salvage values are not effective in the first 5 years of the service life they can be disregarded without serious error, our regular no-salvage formula for the adverse minimum being applicable, it follows that the present special no-salvage formula is applicable over the same range of cases.

[2] To ascertain the implicit gradient (subject only to formula errors) the analyst need only divide the adverse minimum obtained by this formula by n, the service-life estimate. If he wants the gradient without first computing the adverse minimum he can use the formula

$$\text{Gradient} = \frac{c}{n}\left(\frac{2n-1}{n^2} + \frac{i}{1.4}\right)$$

This derivation has, however, no obvious advantages.

challenger in hand. This abuse reaches its worst in the popular rule of thumb that the challenger must "pay for itself" in some very short period such as 2 or 3 years.[1] For another thing, it is difficult with this approach to apply past experience with the defender to projections for the challenger.

This last point needs a word of explanation. Suppose we wish to assume that the challenger will have the same service life as the defender. What this really means is that it will have a life equal to the *correct* or *desirable* life of the defender. But all we know before the replacement analysis is made is the defender's presently attained age, which may be well above or below the correct life we wish to project for the challenger. Unless the analysis happens to be made at the precise moment when the defender becomes replaceable, we are likely, in making the projection, to borrow a service life wide of the mark for defender and challenger alike.

The fact is we confront here something of a dilemma: The only way to find out whether the attained age of the defender is its correct service life is to make a replacement analysis, but to make such an analysis we must first predetermine the service life of the challenger. If for this purpose we borrow the defender's attained age, we are in effect assuming the correctness of that period in order to test it. This problem does not arise in gradient estimating, for if we consider the defender's past gradient a suitable projection for the challenger, it can be readily determined (by dividing the next-year operating inferiority by the attained age) without assuming that this attained age is the correct service life.

Another disadvantage of the service-life approach is its accuracy requirements. For the general run of cases, the service-life formula $c\left(\frac{2n-1}{n^2}+\frac{i}{1.4}\right)$ is much more sensitive to variations in n than is the gradient formula $\sqrt{2cg}+\frac{ic-g}{2}$ to variations in g. This means that as a rule a given relative deviation from the correct life estimate will produce a greater

[1] This rule is discussed at length in Chap. XII.

error in the derived adverse minimum than will a like relative deviation from the correct gradient estimate, hence that it is necessary to estimate the service life more closely than the gradient to stay within any prescribed margin of error in the results of the calculation.[1]

While the service-life approach has these disadvantages, there are many replacement analyses for which its use is clearly indicated. These are analyses in which the defender's gradient provides, for one reason or another, an unsuitable or extremely tenuous basis for estimating a gradient for the challenger. If no other appropriate basis for this estimate is available, and if, therefore, a mere shot in the dark is necessary, it may seem easier to aim this shot at the service life than at the gradient. Whether this is due simply to the greater familiarity of service-life estimates is a fair question, but the fact remains. We should remember, however, that the gradient approach is fundamentally the correct one and should be favored whenever practicable.

Whichever of these approaches is used first in the replacement analysis, it will usually be helpful, by way of checking the results, to see what is implied for the other one. Thus if the adverse minimum is reckoned initially by the gradient formula the analyst may quickly ascertain the implied service life by dividing the estimated gradient into this minimum. Contrariwise, if the first reckoning is by the service-life approach, the implied gradient may be obtained just as readily by dividing the adverse minimum by the assumed service life. By playing both approaches against each other in this way, a better result may often be obtained than can be had by either alone.

[1] Suppose, for example, we have a challenger with a gradient–cost ratio of 5 per cent and a service life, therefore, of 6.8 years, the interest rate being 10 per cent. With a gradient estimate 25 per cent too high, the derived adverse minimum is high by 9 per cent; with a gradient 25 per cent too low, on the other hand, the derived minimum is down by 11 per cent. If, however, the alternative approach is used, a service-life esimate 25 per cent high yields an adverse minimum 15 per cent low, while a life estimate 25 per cent low develops a figure 24 per cent high.

V. SUMMARY

While we cannot arrive by short-cut methods at the exact theoretical figure for the challenger's adverse minimum, we can come close enough for any practical purpose. In the simplest case, involving no salvage value and no capital additions, we can reach the approximate minimum directly, in a single calculation. This is true also when prospective salvage values are too low to be effective. Even if these values do promise to be effective, however, or if capital additions are in prospect, it is possible to ignore these complications, and to use the no-salvage formula nevertheless, whenever the difference between the adverse minimum yielded by that formula and the one obtained by taking the added factors into account is too small to affect the replacement decision. It will be so, we repeat, in the great majority of cases.

The no-salvage formula $\sqrt{2cg} + \frac{ic - g}{2}$ emerges, therefore, as the basic short cut to the challenger's adverse minimum, usable with finality in the absence of capital additions and effective salvage values, usable at least provisionally when they are present. It is a simple prescription, calling for only one estimate, the inferiority gradient, or the average annual rate at which the challenger will accumulate deterioration and obsolescence.[1] Once this estimate is made, the derivation of the adverse minimum is the work of a moment.

In the comparatively infrequent case in which there may be a decisive difference between this adverse minimum and the one obtained by taking salvage values and capital additions into account, the analyst can test with our general formula, spot-checking (ordinarily) the first 5 years of service only. By the cut-and-try technique, unavoidable with this formula, a sufficient approximation to the correct adverse minimum can be easily and quickly disclosed, especially when as often

[1] The acquisition cost, c, is of course known and the interest rate, i, is stipulated. The derivation of the appropriate interest rate will be considered in Chap. X.

happens, the most tentative and preliminary results are sufficient to decide the issue.

Finally, there is available a short-cut formula for the no-salvage case using the service-life approach. This is appropriate when a gradient estimate is impracticable, or as a check on the results of such an estimate in other cases.

With these observations on the character of the available short cuts, we are now ready to consider, in the next chapter, some of the practical problems in their application.

Chapter VIII

PROBLEMS OF ESTIMATION

We have now developed several short-cut formulas or procedures for the derivation of the challenger's adverse minimum. A formula, however, is only an abstract statement of relations among various magnitudes, a mere framework or skeleton. Before it can be applied it must be filled out with actual figures instead of symbols, an operation by no means easy when we are dealing, as we must in replacement analysis, with all the uncertainties of the future. Indeed in this case the preparation of the numerous guesses and estimates required is incomparably more difficult than their subsequent manipulation under the appropriate formula. It is fitting, therefore, that we give close attention to this aspect of the problem.

Since we have just been dealing with procedures for obtaining the *challenger's* adverse minimum, it is appropriate to consider first the estimating problems incident to the application of these procedures, leaving for later the estimates required for the *defender's* minimum. Suppose we proceed accordingly.

I. Estimates Required in Deriving the Challenger's Adverse Minimum

It will be evident from a glance at the short cuts outlined in the preceding chapter that the number of items to be estimated (assuming that the acquisition cost is known and that the interest rate is stipulated) varies from one to three, depending on the circumstances.[1] When it is possible to use

[1] Ordinarily the challenger's acquisition cost requires comparatively little estimating. The price is usually definite, and transportation and installation expenses can usually be approximated. There are cases, however, where a replacement involves considerable out-of-service cost, that is to say, loss from

the no-salvage formula, we need supply only the inferiority gradient (or the life expectancy if the alternative service-life approach is used). If salvage values must be taken into account, these must be estimated in addition to the gradient, at least for the service lives selected for the cut-and-try required in that case. Finally, if capital additions must be included in the reckoning, we have a third item to fill in (a second in the absence of salvage values).

Since the no-salvage formula is our basic short cut, usable in most cases, as we have seen, even when salvage values or capital additions are involved, it is appropriate to begin with the estimation of the one item required for this formula, the inferiority gradient (or the service life if the alternative formula is used).

THE INFERIORITY GRADIENT

Operating inferiority, as we said earlier, is a combination of two elements, deterioration and obsolescence, the one reflecting *internal* change caused by wear and tear, the other reflecting *external* change resulting from product obsolescence, the development of inadequacy, and the improvement of the available mechanical alternatives. How can we tell in advance the average annual rate at which the present challenger will accumulate inferiority? The answer, of course, is that we cannot. The rate is not specifically predictable.

We emphasized when we first introduced the inferiority concept (page 61) that the progress of accumulation is bound to be irregular in individual cases, particularly when obsolescence is the dominant factor, and is bound to differ in retrospect as between machines that appeared in prospect to be closely similar. We concluded, therefore, that a projection for the future must be by intent an expression of probability, not a repetition of any single case as such. This means that in estimating the challenger's future inferiority gradient

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interrupting operations during the change-over. Where this loss is significant, it should be included in the challenger's cost of acquisition; hence an element of estimation does enter in such cases.

the analyst must rely on as broad a base of experience and observation as he can command.

The most logical place to begin, of course, is with the defender concerned in the present replacement analysis, its gradient, as shown by experience to date, being the first consideration. This may be obtained, as we indicated in the preceding chapter, by dividing the current (next-year) operating inferiority relative to the challenger by the attained age. Thus, if the defender's next-year inferiority is $1,500 and if it has been in service 10 years, its gradient is $150 a year, the life-average rate of inferiority accumulation.

When the present defender happens to be one of several similar machines in similar service within one ownership, it may be possible to obtain from the past inferiority accumulation of a number of such machines a typical gradient that can be used, subject to modifications, for the challenger. Suppose, for example, the analyst has available the results of 10 recent analyses involving machines similar to the present defender:

Case	Period of service prior to analysis, years	Next-year operating inferiority at time of analysis	Gradient
1	10	$1,500	$150
2	14	1,800	128
3	11	1,200	109
4	8	1,200	150
5	15	1,800	120
6	13	1,800	138
7	9	1,400	156
8	12	1,500	125
9	10	1,300	130
10	11	1,600	145
			Average, $135

Even when such an average of past gradients is available, it is not something to be used uncritically or by rote. The outlook for the challenger may differ materially from the past experience of recently retired machines. If this caution

properly applies to the use of an average, it applies even more forcefully when, as in most cases, the analyst must rely for historical data primarily on the record of the present defender. All he can do under these circumstances is to evaluate the elements of likeness and difference as best he can and project the challenger's gradient accordingly.

While such a projection may seem difficult, it is no more so in most cases than other forecasts incident to the work of an engineer. The result, in any event, is only an informed guess. Fortunately, a high degree of exactitude is unnecessary, since moderate variations in the gradient estimate have a comparatively slight effect on the challenger's adverse minimum, the object of the whole calculation. Thus in ordinary no-salvage cases a 25 per cent variation above or below the correct gradient estimate will result in an error of about 10 per cent in the adverse minimum. A reasonable approximation is as good, for practical purposes, as a more refined calculation.

Before we leave the subject of gradient estimating, it is well to add two further comments. The first has to do with the rate of activity assumed. If the challenger's operating rate, or use intensity, is expected to be variable, the analyst should base his calculations on a normal, or representative, rate—generally, of course, some kind of average drawn through the anticipated fluctuations. The second comment concerns the assumed pattern or composition of operations. If the job for which the challenger is under consideration is by nature shifting and varied, the gradient should be estimated on a representative pattern of work assignments.

THE SERVICE LIFE

We indicated in the preceding chapter (page 110) that while the gradient approach is recommended whenever practicable, there are numerous situations where the basis for a gradient estimate is inadequate and where it may be desirable, or even necessary, to resort to the alternative service-life approach.[1] The challenger may differ so radically from

[1] This approach, it will be recalled, is an alternative for the no-salvage case only.

the defender, mechanically, technologically, or in respect of its productive capacity, that the defender's past inferiority accumulation may offer little clue to the future. In such cases the analyst may feel more confidence in a service-life estimate than in a gradient projection.

In making such estimates, it is necessary to remember that only the challenger's *primary* service life is at issue, that is to say, the period prior to its first replacement. This may or may not coincide with its entire life span, depending on whether it goes after the initial replacement to the scrap heap or to further service in some other capacity. It is necessary to remember also that the primary service life should be estimated *in full*, without the conventional foreshortening so often employed to allow for future obsolescence and other hazards. As previously indicated, our short-cut formula for the service-life approach allows for a constant accumulation of deterioration and obsolescence; hence no additional allowance is called for in the service-life estimate itself. This estimate should rest on a realistic appraisal of the primary-service expectancy of the challenger in hand, uninfluenced by conventional pay-off periods or other stereotypes.

Beyond this general admonition we cannot usefully go, except to remind the analyst of a point made in the preceding chapter, that the service-life formula is quite sensitive to variations in the life estimate. This means that the estimate should be considered carefully and with due circumspection. It means also that it should be checked, as standard practice, by reference to the gradient estimate which it implies.[1] If this gradient appears out of line with reasonable expectations, the life estimate can be adjusted until the most plausible combination ot service life and gradient is obtained.

SALVAGE VALUES

Heretofore we have employed the term "salvage value" generically without distinguishing two kinds of value which

[1] As we indicated earlier (p. 59) this estimate is readily obtainable by dividing the estimated life into the adverse minimum derived by the service-life formula.

it is necessary to consider separately now that we confront the practical problem of estimation. The first kind is value for sale or disposal *outside* the enterprise. The second is value for alternative use *within* the enterprise. Obviously the latter, which we may call "conversion value," should be used in preference to resale value whenever it is the higher of the two.

While it makes no difference to the replacement formula which type of value we are dealing with, since both are *applied* in the same way, it does make a difference to the estimating procedure, since they are *derived* by quite dissimilar methods. Obviously, the resale value of a machine is obtained by consulting the market, but its conversion value can be had only by internal analysis.

We can state the problem of conversion value in the form of a question. If the present challenger is installed in the service for which it is now being considered (this we may call the primary service), what will be its value as time goes on for transfer to other service (secondary service) in the same ownership when, as defender, it is challenged for this primary service by new machines? This is equivalent to asking what the enterprise can afford to pay for it at various points of future time as the challenger for the best secondary service then available.

However the problem is phrased, it is quite obvious that the estimation of future conversion values is difficult. While it is by no means easy to project resale values in a replacement analysis, the past values of similar facilities, on which projections for the future must necessarily be based, are at least a market phenomenon, ascertainable, as a rule, within a reasonable margin of error. But when the projection concerns conversion values, the basis of estimation is more elusive. For conversion values are not recorded in the market. They can only be deduced from the analysis of particular cases.

Theoretically it should be possible to develop a formula for these values, but it would be too complicated, with too many

fixed assumptions, for general use.[1] In practice the analyst must rely when necessary on an informed guess. Under the circumstances it is fortunate that so far as the challenger is concerned the necessity does not arise too often. For as we saw in the preceding chapter, its salvage values can be ignored save in cases in which they promise to swing the replacement decision. If these cases are relatively few when we include both types of salvage value, they are necessarily much fewer still for conversion value alone.

When it appears that challenger conversion values simply must be estimated, the analyst will do well to remember two points: (1) It is unnecessary, as a rule, to project them beyond the first 5 years of service. For as we saw earlier, if salvage is not effective during that period it can ordinarily be disregarded, leaving the adverse minimum to be computed by the no-salvage formula. (2) The guessing range is limited on the one side by the challenger's future resale values and on the other by what it would cost at the future points of reference to acquire a facility of like character and condition. For obviously if conversion values are *below* resale values it will pay to sell rather than to convert, while if they are *above* the purchase prices of comparable facilities it will pay to buy. The former are therefore the floor, and the latter the ceiling, of the guessing range.

CAPITAL ADDITIONS

There are some types of equipment with a fairly regular and predictable pattern of capital additions over the service life. These normally consist of major renewals (heavy repairs) recurring at more or less infrequent intervals. When the current challenger is of this type and when the additions promise to have a decisive effect on the calculation of its adverse minimum, the analyst has one more set of estimates to make. He must supply the approximate amounts involved

[1] Moreover, the development of such a formula would carry us into the theory of secondary replacement, an inquiry we renounced at the beginning of this investigation (p. 25). For further discussion see p. 263.

and the service years in which they are expected to occur. He can then apply his figures in accordance with the procedure suggested in the preceding chapter.

We have no special tips on how to make the estimates. The analyst must turn to account whatever relevant experience he can find. We do have, however, a word of admonition. The reckoning of capital additions should *not* turn on their accounting treatment. They may be expensed in one case and capitalized in another, with no effect on the result for our purpose. In general, the estimates should include all extraordinary, or nonroutine, repairs and renewals, so far as they are predictable, routine maintenance being covered in the estimate of the inferiority gradient.[1]

II. Estimates Required in Deriving the Defender's Adverse Minimum

We have repeatedly stated that replacement is signaled whenever the defender's adverse minimum rises above the challenger's. To put it otherwise, the signal comes when the lowest time-adjusted average of operating inferiority and capital cost obtainable for any future period from the defender exceeds the lowest average of these factors obtainable for any such period from the challenger. The replacement analysis is basically a comparison of these two magnitudes. It follows that the estimates incident to the determination of the defender's minimum are no less important than the ones we have been considering.

A SIMPLIFYING ASSUMPTION

Though no less important, these estimates are, fortunately, considerably less difficult. For as we observed earlier (page 85), it is usually safe to assume that by the time a machine has become an appropriate object for a challenge its total of operating inferiority and capital cost for next year is lower than the annual average of these magnitudes obtainable for

[1] The standard assumption that the gradient is a constant implies the exclusion from the reckoning of operating inferiority of the sporadic and irregular elements covered under capital additions.

any longer period. When this assumption applies, the next-year figure is of course the adverse minimum itself. It follows that the estimates incident to the derivation of the minimum need relate to 1 year only. This simplifies the estimating problem enormously.

The reason for assuming that the defender's next-year total of operating inferiority and capital cost is its minimum for the future we mentioned briefly in the earlier discussion. Its operating inferiority normally rises more or less continuously. So far as this factor is concerned—and it is the only component of the adverse minimum in the absence of salvage value or future capital additions—the assumption is generally acceptable. When it needs qualification, it is either because salvage values (plus interest thereon) are falling faster than operating inferiority is rising or because next year's capital additions are heavier than those of succeeding years, or for both reasons combined. Suppose we consider these complicating factors briefly.

SALVAGE. The chance that salvage value (and interest thereon) will decline faster than operating inferiority will rise is considerable only when the defender is relatively new at the time of the challenge and when salvage value is, accordingly, still high. As the value works down and as its rate of decline (together with the associated interest charge) abates, this chance becomes continually smaller. There is less and less risk, therefore, that future periods longer than a year will show a combined annual average of operating inferiority and capital cost below the figure for next year alone.

CAPITAL ADDITIONS. When we turn to capital additions, we have a more difficult problem. The replacement analysis is frequently precipitated by the fact that the defender confronts the necessity for heavy repairs or renewals. If these are charged in full against next year, they may easily give rise to an adverse figure for that interval materially above the average obtainable for a longer period of time. (The risk is minimized, of course, to the extent that the additions are reflected in the year-end salvage value, but this reflection

may be partial or nonexistent.)[1] The solution of the problem lies in the abandonment of the simplifying assumption when sizable capital additions are impending and the computation of the defender's adverse average for a period of further service longer than one year, the period being dictated, in general, by the time expected to elapse between the renewals now contemplated and the next round of substantial additions. For example, if these renewals will keep the defender in service with only current repairs for another 3 years, this is the logical period for the reckoning, the assumption being that if the adverse average for this interval is not the adverse minimum itself, it is close enough for all practical purposes.

The calculation of this adverse average can be made by an adaptation of our general short-cut formula,

$$\text{Adverse average} = \frac{g(n-1)}{2} + \frac{c-s}{n} + \frac{i(c+s)}{2}$$

The adaptation consists of adding the defender's next-year operating inferiority, making the right side of the equation for the present purpose[2]

$$\text{Next-year inferiority} + \frac{g(n-1)}{2} + \frac{c-s}{n} + \frac{i(c+s)}{2}$$

when n is the period of additional service, c the sum of capital additions and present salvage value (the present investment), s the salvage value at the end of the period, and g the inferiority gradient during the period.

Suppose we have a 10-year-old defender which requires renewals of \$800 to keep in service, no further important additions being in prospect for 4 years. Next-year operating inferiority is \$1,700. The gradient estimate is \$170—merely a projection of the average rate of inferiority accumulation in the

[1] A higher year-end value, by reducing the loss of salvage, helps to offset the effect of the additions on the total of operating inferiority and capital cost for the year.

[2] As originally developed, the formula was adapted to a challenger, whose next-year operating inferiority is, by assumption, zero. When applied to a defender, whose next-year inferiority is of course a sizable magnitude, it is necessary to add this magnitude to the formula.

past ($1,700 ÷ 10). Present salvage value is $500 and will be $200 at the end of 4 years. Solving for the adverse average, we have[1]

$$1700 + \frac{170 \times 3}{2} + \frac{1300 - 200}{4} + \frac{.10(1300 + 200)}{2} = \$2,305.$$

OPERATING INFERIORITY

The estimation of the defender's next-year operating inferiority to the challenger is a preeminently practical task, to be satisfactorily accomplished only by men intimately familiar with the operations concerned, and all we can hope to do here is suggest a few guiding principles.

The first is that the analysis of the defender's operating inferiority should not be limited, as it often is, to *cost* comparisons alone. As we indicated in Chap. III, operational differences between two machines (or between two groups of machines when a group replacement is at issue) may lie either (1) in the quality and character of the service rendered, or (2) in the cost of obtaining it. In the first case the difference is reflected in the *receipts* of the enterprise; in the second it is reflected in its *expenditures.* Obviously a challenger superiority in the form of increased receipts is just as valuable, dollar for dollar, as an advantage in the form of reduced expenditures. *The comparison of challenger and defender should include both.*

A new machine (or group of machines) may permit an improvement in the product turned out, through better design, different materials, or greater precision of manufacture. It may permit a wider variety of products. It may

[1] A more rough-and-ready but less accurate procedure in the case of defender capital additions is to compute next-year capital cost by including only that portion of the addition deemed properly allocable to it and by ignoring the effect of the addition, if any, on the salvage value at the end of the year. In the case just cited, for example, we might allocate $200 of the addition to next year ($800 ÷ 4) and estimate salvage at the end of the year at $350. Capital cost for the year would then by $200 for additions, $150 for loss of salvage, and $130 for interest, a total of $480. Added to the next-year operating inferiority of $1700, this would yield a defender's adverse minimum of $2,180 against $2,305 by the more exact method. This short cut normally yields, as here, too low a figure.

provide greater capacity. It may be more reliable, with less risk of outages and shutdowns. Such revenue-increasing advantages figure to some degree in a large proportion of replacement situations. If we may judge from the literature of replacement practice, however, we infer that whenever cost saving is the primary consideration these incidental revenue advantages are likely to be treated merely as "imponderables" or "irreducibles." Elements so treated rarely bring their full weight to bear on replacement decisions; indeed they are often ignored unless the case is otherwise a close one. Yet they may be important enough if given a dollar-and-cents evaluation to swing the balance in many decisions that now go in favor of the defender.

Our second point has to do with the reckoning of cost saving itself. In some cases the only element of challenger operating advantage (defender inferiority) taken into the estimates is the saving in direct labor cost. This rarely does justice to the challenger even when revenue-increasing advantages are wholly absent. It ignores the possibility of cost saving through lower maintenance, decreased spoilage of materials, reduced overhead,[1] lower power consumption, reduced toolroom costs, increased convenience and flexibility, greater reliability,[2] better worker morale, and what have you. The relegation of these other elements of cost saving to the limbo of "imponderables" results, as we observed in the preceding paragraph, in a gross detraction from their proper influence. *If they are significant, they should be the subject of specific estimates.* Well-considered estimates, even if decidedly conjectural, are almost certain to add up to a more rational result than the usual practice of hunching the effect of all "imponderables" in one lump.

[1] We may comment in this connection on the assumption, sometimes made in analyses that go beyond the saving of direct labor, that overhead cost will be reduced proportionally. There is no reason whatever to assume this. Specific estimates of saving (or increased cost) should be made whenever the amounts involved are significant.

[2] This is an example of an advantage that may be either revenue-increasing or cost-reducing, or both. We do not care how the advantage is classified so long as it is reflected in the calculation.

Our third observation concerns the rate of activity to be assumed in reckoning defender inferiority. When we were considering some time ago the operating rate appropriate for estimating the challenger's inferiority gradient, we suggested an average for its service life, or some "normal" approximating it. It may appear that since we are estimating the defender's inferiority for next year, we should use the operating rate anticipated (for the defender) for that period only.[1] This is satisfactory if the next-year rate is lower than that expected for later years, but in the reverse case it is better (in view of our simplifying assumption) to use an average rate for a somewhat longer period.[2]

SALVAGE VALUE

We have made the point on several occasions that the defender, unlike the challenger, may have no capital cost at all. In this case its adverse minimum is its next-year operating inferiority alone. When it does have such cost, it is because of salvage value or capital additions.[3]

When salvage value is present, the analyst must estimate it as of now and a year hence, thus disclosing the loss of value during the year. In the absence of additions, this loss, together with interest on the present value, is the next-year capital cost. Suppose, for example, the opening salvage is adjudged to be \$1,800, with a reduction to \$1,500 at the end of the year. Interest being 10 per cent, we have \$300 + \$180 = \$480.

Obviously it is far easier to estimate the defender's present

[1] We insert the parenthesis (for the defender) because the operating rate projected for the defender may be different, especially if expressed in terms of *output*, from the rate used in estimating the challenger's inferiority gradient. As we shall see shortly, the two machines may be of different size and capacity.

[2] If the rate projected for next year is substantially higher than anticipated for the immediately succeeding years, the next-year operating inferiority computed on that rate may be above the average obtainable for a longer interval, hence may not be (with capital cost) the adverse minimum which the assumption makes it. It may be added that if the operation is characterized by changing work assignments, the defender's inferiority should be figured from a representative crosssection of such assignments.

[3] It may be pertinent to remind the reader again (see p. 38) that the book value has no bearing on the replacement analysis.

salvage value and the next-year runoff thereof than to estimate the challenger's values over the 5-year period we have suggested for use when these values must be taken into account. On the other hand, it is necessary to make the defender estimates in a much higher proportion of cases. It will be recalled that challenger salvage values can be disregarded in the great majority of analyses, the adverse minimum by the no-salvage formula being in general a satisfactory approximation to the correct result. But this is not true of the defender. Unless its salvage value is nominal, it should be taken into account.[1]

CONVERSION VALUE AGAIN

When the defender's salvage takes the form of resale value, it is ordinarily not difficult to estimate, but when the machine is worth more for some secondary use in the same ownership than it is in the market, we have once more the knotty problem of conversion value. While the problem is somewhat simpler for the defender than for the challenger, since it involves conversion values at only two points in time—the present and a year hence—it remains nevertheless exceedingly intractable. Again the analyst can only make his best guess, remembering, as before, that the guessing range is bounded at the bottom by the resale value and at the top by the cost of acquiring a comparable facility from the outside. Fortunately, this range is narrow enough in most cases so that variations within it have comparatively little effect on the results of the replacement analysis. There is seldom, therefore, any reason for the analyst to lose sleep over his conversion-value estimates.

While the problem is not too troublesome as a rule, we may venture to suggest a possible alternative procedure, usable in the case of the defender, which avoids the estimation

[1] The disregard of challenger salvage results, as we have seen, in too *high* an adverse minimum. The disregard of defender salvage, on the other hand, yields a minimum too *low*. The difference is due to the fact that in the first case we disregard only the terminal salvage values. To put it otherwise, the omission of challenger salvage leaves the acquisition cost as the capital charge, while the omission of defender salvage eliminates capital cost entirely.

of conversion value entirely. It substitutes for the defender's next-year capital cost (the derivation of which requires the conversion-value estimates) its next-year *operating* advantage over the machine it displaces in secondary service, plus the saving in capital cost (if any) from the disposal of that machine. If the primary replacement gives rise, as it sometimes does, to a whole series of secondary replacements, it is the combined next-year operating advantage from the entire series that is taken, plus, in this case, the saving in capital cost (if any) from the disposal of the machine or machines released at the end of the chain.

To illustrate by a hypothetical case, we have, let us say, a primary defender, *A*. If replaced, this defender is usable in another function within the same ownership, for which it becomes, of course, the challenger. Relative to the secondary defender, *B*, it has a next-year operating advantage of $1,000. If replaced, *B* in turn becomes the challenger for the job held by another secondary defender, *C*, over which it has a next-year advantage of $500. If replaced, *C* can be used for the job now held by *D*, for which it has a next-year advantage of $300. Finally, *D* can be sold for $1,000 now or for $800 a year hence, thus saving a next-year capital cost of $300 ($200 loss of salvage and $100 interest). The sum of the three operating advantages plus the saving in capital cost is $2,100. This can be used in lieu of *A*'s next-year capital cost as derived from conversion-value estimates.[1]

Whether this alternative procedure offers any advantages over the procedure based on conversion-value estimates, the reader may judge for himself. In any event, it is available for those who prefer it.

[1] Even this substitute for defender capital cost is subject, however, to upper and lower limits. It cannot be *less* than next-year capital cost derived from resale-value estimates, nor *more* than next-year capital cost on a comparable machine if purchased in the market.

While it can be shown that under our standard assumptions the alternative procedure yields the same result as the regular one *if the latter is applied with a correct estimate of the primary defender's conversion value*, the demonstration of this proposition involves a range of theory not hitherto presented in this discussion. For this reason we shall simply leave it without proof.

DERIVATION OF DEFENDER'S ADVERSE MINIMUM ILLUSTRATED

By way of illustration, suppose we work through the derivation of the defender's adverse minimum in two hypothetical cases, in the first of which the challenger has the same

CASE A

I. Operational analysis

	Estimated next-year advantage: Challenger	Estimated next-year advantage: Defender
a. Revenue items:		
Superiority of product	$ 250	
b. Cost items:		
Direct labor	1,200	
Indirect labor	150	
Spoilage of materials	50	
Maintenance	300	
Down time	50	
Power	.....	$ 50
Tool costs	30	
Floor space	100	
Property taxes	.....	50
Insurance	.....	30
All others	100	
Total	$2,230	$130

Net challenger superiority (defender inferiority) $2,100

II. Defender capital cost analysis

Present salvage value	$2,500		
End-of-year value	2,100		
Loss of salvage	.....	$400	
Interest on present value	.....	250	
Capital cost	.....	....	650
Defender's adverse minimum	.....	....	$2,750

productive capacity as the defender; in the second of which its capacity is substantially larger. We shall express the operational comparison in terms of *superiority* rather than of *inferiority*, since this is the more usual procedure in replace-

ment analysis. Obviously the magnitude is the same viewed from either side.

Our second case assumes a challenger with a substantially larger productive capacity than the defender's. It assumes further that this added capacity is currently and prospectively usable, a most important qualification. Unlike the first case, which compared challenger and defender at the same rate of output, this one compares the defender at one rate with the challenger at a different, and higher, rate. The full measure of the defender's operating inferiority in the present instance

CASE B

I. Operational analysis		
	Estimated next-year advantage	
	Challenger	Defender
a. Revenue items:		
Superiority of product	$ 300	
Increased output	3,000	
b. Cost items:		
Direct labor	.....	$ 300
Indirect labor	.....	50
Spoilage of materials	50	
Materials requirements	.....	400
Maintenance	300	
Down time	50	
Power	.....	100
Tool costs		
Floor space	50	
Taxes	.....	100
Insurance	.....	50
All other	100	
Total	$3,850	$1,000
Net challenger superiority (defender inferiority)		$2,850
II. Defender capital cost analysis		
Capital cost (assumed to be same as in previous example)		$ 650
Defender's adverse minimum		$3,500

is the amount by which the use of the challenger, at the output it makes possible, increases the revenue and decreases the costs of the operation as compared with the use of the defender at the output which it makes possible.[1]

This particular setup has no special significance and can be modified indefinitely to fit the case. It does illustrate, however, the importance of taking into account both revenue and cost differences between challenger and defender. As we emphasized earlier, this is fundamental.

III. Expansion Analysis

The second illustrative example just given, which presents an analysis involving partly replacement and partly expansion, invites the consideration of the following question: If our procedure can be used to test the advantage of a proposed equipment acquisition in a mixed situation of this kind, why can't it be used for the same purpose in a situation involving expansion only? As a matter of fact it can be. It may be worth while, therefore, to consider this application for a moment even in a work whose main interest is replacement, or reequipment, analysis.

When the proposed machine represents a net addition to capacity, hence does not dislodge any existing installation from its present function, it may seem at first glance that we have a "challenger" but no "defender." This impression is of course mistaken. The defender in this case is fundamentally the same as in any other: the *status quo*—in plain English, the existing setup. Here, as elsewhere, the question is whether to continue the present setup as is or to add the new machine to it.

[1] It may be remarked in passing that when, as here, the defender is suffering from the type of obsolescence known as "inadequacy," that is to say, when its capacity has come to be insufficient because of external growth or change, unusual caution is required in deducing the challenger's inferiority gradient from the history of the defender. For the challenger may or may not promise to accumulate inadequacy in service as the defender has done. If it does not, the defender's gradient, based in part on such accumulation, may be too high. This is one of the situations in which the service-life approach to the challenger's adverse minimum may be indicated.

Whether this machine displaces another one wholly, partially, or not at all is a matter of detail.

In the absence of displacement, there can be, of course, no saving in the capital cost of carrying the existing setup by reason of the proposed addition. Since no part of this setup can be sold or transferred to other useful functions within the ownership, it follows that the next-year advantage from the addition is an operating advantage only. *The expansion is signaled, therefore, when the net next-year operational gain from the addition of the new machine to the existing setup exceeds the adverse minimum of that machine.*

EXAMPLE

Suppose we wish to test the propriety of an immediate expansion through the purchase of a new unit or units of equipment. The next-year operational analysis appears as follows:

	Estimated next-year advantage	
	With added equipment	With present setup
a. Revenue items:		
Increased output	$15,000	
Quality of product	500	
b. Cost items:		
Direct labor	....	$2,700
Indirect labor	....	800
Materials	....	3,000
Floor space	....	200
Maintenance	....	300
Power	....	400
Taxes and insurance	....	700
Other (incl. overhead n.e.s.)	....	600
Total	$15,500	$8,700
Net challenger superiority (defender inferiority)		$6,800

The cost of the proposed equipment, let us say, is \$25,000, and it is given a probable service of 12 years. Using the service-life formula for the adverse minimum, $c\left(\frac{2n-1}{n^2}+\frac{i}{1.4}\right)$, we have

$$25{,}000\left(\frac{24-1}{12^2}+\frac{.10}{1.4}\right)=\$5{,}779$$

The adverse minimum of the proposed equipment being \$5,779 as against a next-year operational advantage of \$6,800 from its acquisition, the expansion is clearly indicated.[1]

IV. Procedure for Very Short-Lived Equipment

With this digression, we return now to replacement analysis. The reader will have noted that all of our illustrations thus far relate to equipment with a substantial service life, whether past or future. This is no accident. For the standard analytical procedure we have set up may need to be modified for very short-lived equipment.

When the challenger has a prospective service life of say 2 or 3 years, it may not be satisfactory to deal, as we do, in time units of an entire year; the analyst may wish to reckon in months or quarters.[2] Neither is it always satisfactory to assume, as we also do, that if the defender is not replaceable now it will continue in service for at least a year. It may be desirable to test for shorter periods. Finally, and more important, it may be undesirable when the service life is very short to assume that the challenger will accumulate deterioration and obsolescence at a constant rate. Instead, the analyst may wish to substitute specific estimates of inferiority for the figures developed by the constant-gradient assumption.

For a challenger with an economic service life of say 5 years or more, it usually makes very little difference whether

[1] It is clearly indicated, that is to say, on the basis of our standard assumptions, which remain the same for this expansion case as in the replacement cases previously discussed.

[2] The term "service life" continues to refer of course to the period before the primary replacement (p. 24). We have no concern with the challenger's career beyond that period.

we make specific year-by-year estimates of its operating inferiority or simply assume a constant gradient, provided, of course, that the *average* rate of accumulation is the same in both cases.[1] But with shorter service lives the difference may be fairly substantial. If the need for specific estimates is greater in this case, so also is the possibility of making them. For the analyst may be able to estimate a few years ahead when he would be at a loss for more distant projections.

Whether it is desirable to strain for such specific estimates of inferiority accumulation in lieu of our usual constant-gradient assumption depends on the characteristics of the equipment involved and on the degree of exactitude demanded by the replacement analyst. The same can be said of the alternative of cutting up time into months or quarters instead of the annual intervals employed by our standard procedure. In some cases these refinements will make a significant difference; in others they will make virtually none. We point them out, not to disparage our procedure generally as applied to short-lived equipment, but to indicate their availability for those who wish to try them.

Since these refinements represent a departure or deviation from our standard procedure, we shall not interrupt its exposition to develop them at length. For those who wish to pursue the subject, however, there is an additional discussion on page 265.

[1] For illustration, see p. 264.

Chapter IX

THE PROCEDURE APPLIED

This discussion has now carried us over a long and arduous road. We began by considering replacement analysis as an abstract theoretical problem. We then developed certain standard assumptions to simplify the analysis. We followed with a mathematical procedure for the application of these assumptions. Thereafter we undertook to simplify this procedure by the substitution of short-cut approximations. Finally, we considered the estimating problems incident to the use of these short cuts. With this preparation we are now ready to get down to cases. We propose in this chapter to apply our procedure to a number of realistic situations.

Before we do this, however, it may be well, as a hedge against possible misunderstanding, to reiterate once more a point that may seem to have been sufficiently belabored already, namely, that no standard analytical framework or procedure like the one we have developed can be applied without the use of discretion by the analyst. Such a procedure, we repeat, can yield a first approximation. It can make a prima-facie case. But the final decision must be, in the nature of things, an act of judgment. The analyst must use judgment in compiling the data and making the estimates that enter into the application of the procedure; he must use it again in accepting or rejecting the course of action suggested by the result. It follows that the solutions indicated by the applications presented below are of this preliminary, or prima-facie, character only.[1]

Another observation is appropriate at this point. The really difficult part of most replacement analyses is the

[1] For a brief discussion of the "shading" of the results of our standard procedure, see Chap. XV, p. 234.

compilation of the detailed data and estimates underlying the figures which finally emerge in summary form for the application of the formula. This application represents in fact the last step in the whole operation. Since the examples we are about to offer have to do only with this final step and do not include the underlying work sheets, they do not purport to be complete replacement analyses. Hence they illustrate primarily the organization and manipulation of the summary estimates, once these have been derived.

A few more introductory comments are in order. First, our examples assume that the challenger has been correctly chosen. We simply take for granted that it is the best available alternative to the equipment it is proposed to replace, or (if an expansion rather than a replacement is at issue) that it is the best available addition to the existing setup. Second, for expository reasons we shall carry out the calculation in full in each case, despite the fact that the result is often evident from the most casual glance at the principal figures. In practice, the analyst can often come to the decision without considering small items in the picture and without completing the computation. Third, it should not be inferred from the fact that most of our examples signal replacement (or expansion) that our formula is biased toward this result. The preponderance of positive signals is a reflection simply of the character of the cases that happened to be submitted for use in this chapter. With cases of a different character the preponderance could, of course, be reversed. Fourth, we shall assume a cost of money (interest rate) of 10 per cent throughout the discussion. In practice (as indicated in the next chapter) the appropriate rate will differ from company to company and from time to time for the same company. In using 10 per cent, therefore, we in no way imply that this is "correct" or "normal"; it is simply a matter of convenience.

One final point: It will be observed that notwithstanding the order followed for expository purposes in the preceding chapters our first operation in each analysis is to obtain the *defender's* adverse minimum. This operation divides in turn

into two separate steps: (1) the derivation of the next-year operating inferiority of the defender to the challenger (the challenger's operating advantage), and (2) the derivation of the defender's next-year capital cost. Only when this operation has been completed do we turn to the calculation of the *challenger's* adverse minimum.[1]

Let us begin with a few straight replacement cases, that is to say, cases in which the challenger will merely do better the same job now done by the defender and in which the expansion of capacity does not enter into the calculation.[2]

I. Straight Replacement

1. PLANER

A metalworking plant is considering the purchase of a 36-inch by 16-foot open-side planer to replace a 19-year-old unit of comparable size. The installed cost is $29,860. It is estimated that the present machine can be sold in the second-hand market for $6,000.

The new planer has a tool lifter which operates on the return stroke and makes it possible to use carbide cutting tools. Moreover, it makes available the high speed of 180 feet per minute on the cutting stroke and 300 feet on the return stroke. These advantages offer a saving of direct labor on the planing operation estimated at $1,525 a year. This, however, is only part of the picture. Because of improved lubrication, nonmetallic ways, and such features as push-button control to slow the feed over hard or heavy work, the new machine gives much greater precision and a smoother surface. This eliminates a considerable amount of secondary grinding and scraping, with an estimated direct labor saving of $2,500 annually. The probable next-year saving in main-

[1] In taking the sum of the two derivations as the defender's adverse minimum, we are of course implying the validity of our standard simplifying assumption that the combined operating inferiority and capital cost for next year is lower than the annual average of these magnitudes for any longer period. This assumption, as we have seen, is sometimes questionable.

[2] The expansion may be excluded either because the challenger has no greater capacity than the defender or because greater capacity is not presently needed.

tenance with the new machine is put down at $200. To this is added, finally, a small saving in required floor space, valued at $60. On the debit side there is an increase, estimated at $230 annually, in property taxes and insurance. In tabular form, the next-year operational analysis appears, therefore, as follows:

	Next-year operating advantage	
	Challenger	Defender
Direct labor on the planing operation	$1,525	
Direct labor on succeeding operations	2,500	
Maintenance	200	
Floor space	60	
Taxes and insurance	.....	$230
Total	$4,285	$230
Net challenger advantage (defender inferiority)		$4,055

Since the present salvage value of the old planer is estimated at $6,000 and since this is expected to be $5,000 a year hence, the capital cost of keeping it another year is $1,000 in loss of salvage, plus $600 interest, or $1,600. Adding this to the operating inferiority of $4,055, the analyst obtains

Defender's adverse minimum = $5,655

Having derived the defender's adverse minimum, the analyst turns next to the challenger's. Since the case seems appropriate for the inferiority-gradient approach, he first computes the defender's past gradient, which turns out to be about $210 a year ($4,055 ÷ 19). Accepting this as a reasonable projection for the challenger, he inserts this figure in our gradient shortcut, $\sqrt{2cg} + \frac{ic - g}{2}$, solving as follows:

$$\sqrt{2 \times 29{,}860 \times 210} + \frac{.10(29{,}860) - 210}{2} = \$4{,}929$$

With the defender's adverse minimum of \$5,655, the corresponding figure of \$4,929 for the challenger appears to signal replacement decisively. It is unnecessary, therefore, to inquire whether the challenger's adverse minimum might be even lower if its future salvage values were taken into account. This is particularly true since the challenger has certain advantages over the defender for which no "dollars-and-cents" estimates are available. Thus, for example, the new planer, being of the open-side type, can take wider work than the old one. When such imponderables are taken into account the case is doubly clear.

2. MILLING MACHINE

A milling-machine manufacturer is considering the construction of a new and greatly improved machine to slot milling cutters, this machine to replace the existing unit, now 12 years old. Total cost will be approximately \$60,000. Salvage value of the old unit is negligible.

The next-year saving of direct labor in slotting and in subsequent operations in the manufacture of cutters is estimated at \$13,700. To this are added savings of \$1,000 in indirect labor, \$250 in maintenance, and \$100 in floor space. Since the company is a producer of milling machines as well as cutters, the new unit will have considerable value for display and selling purposes, the next-year estimate of this value being \$500. Finally, there is a debit item of \$500 for increased taxes and insurance. Thus the operational comparison lines up as shown in the Table on page 139.

As the defender has no appreciable salvage value, no saving in capital cost is obtainable from its replacement; hence

$$\text{Defender's adverse minimum} = \$15{,}050$$

Since the old machine has accumulated an operating inferiority of \$15,050 over 12 years, its gradient is about \$1,250 a year. This the analyst considers somewhat too high for the new machine, for which he is inclined to anticipate

	Next-year operating advantage	
	Challenger	Defender
Direct labor	$13,700	
Indirect labor	1,000	
Maintenance	250	
Floor space	100	
Display and sales promotion	500	
Taxes and insurance	....	$500
Total	$15,550	$500
Net challenger advantage (defender inferiority)		$15,050

a less rapid obsolescence than has overtaken the incumbent. For this reason he cuts the projected gradient down to $1,000 a year, solving for the adverse minimum as follows:

$$\sqrt{2 \times 60{,}000 \times 1{,}000} + \frac{.10(60{,}000) - 1000}{2} = \$13{,}454$$

This gradient implies a no-salvage service life of 13.5 years (13,454 ÷ 1,000), which the analyst finds generally acceptable. Replacement appears to be indicated by a safe margin.

3. TEXTILE MACHINERY

A textile mill is reviewing the advantages of buying a new mechanical layout to replace its present spooling and warping equipment. The new layout consists of 2 automatic spoolers, 1 high-speed warper, 1 combination shaftless ball and section beam warper, and 1 tailings machine, costing, together with the necessary attachments and accessories, $107,700. The existing equipment has an estimated resale value of $7,500.

The new layout will deliver the present volume of production with 16 workers as against 37 now required. The direct labor saving is estimated at $27,100 a year, the indirect saving at $4,000. The saving in maintenance looks like $1,200. With lesser differences added, the operational analysis follows:

	Next-year operating advantage	
	Challenger	Defender
Direct labor	$27,100	
Indirect labor	4,000	
Maintenance	1,200	
Power	....	$ 150
Taxes and insurance	....	850
Total	$32,300	$1,000
Net challenger advantage (defender inferiority)		$31,300

The next-year runoff in the salvage value of the old equipment is estimated at $1,500, which together with interest of $750 on the present value makes the cost of keeping it $2,250. Adding this to the operating inferiority, the analyst has

$$\text{Defender's adverse minimum} = \$33{,}550$$

The old equipment is of various ages, averaging around 20 years, and since its next-year operating inferiority is $31,300, a gradient in excess of $1,500 a year is indicated (31,300 ÷ 20). If this is applied to the new equipment the adverse minimum comes out as follows:

$$\sqrt{2 \times 107{,}700 \times 1{,}500} + \frac{.10(107{,}700) - 1{,}500}{2} = \$22{,}610$$

This gradient implies a service life of about 15 years (22,610 ÷ 1,500), which the analyst considers on the low side, but since a lesser gradient yielding a longer life would only lower further an adverse minimum which already signals replacement loudly, it is unnecessary to refine the calculation. Nor is it necessary to consider the untabulated advantages from the replacement, which are substantial.

4. GRINDER

A machine-tool builder is reviewing a proposal to replace a 10-year old grinder by a new one costing $16,000. The old unit is salable for $2,500.

Annual labor saving from the replacement is estimated at \$1,050 direct and \$100 indirect. The saving in maintenance is \$300. Since the company is in the business of selling machine tools, it is willing to allow \$200 a year for the advertising and selling advantage of having the up-to-date grinder in its plant. The operating comparison works out, therefore, as follows:

	Next-year operating advantage	
	Challenger	Defender
Direct labor	\$1,050	
Indirect labor	100	
Maintenance	300	
Sales promotion	200	
Taxes and insurance	.....	\$100
Total	\$1,650	\$100
Net challenger advantage (defender inferiority)		\$1,550

The next-year capital cost of keeping the defender is estimated at \$300 for the decline in sale value and \$250 for interest, a total of \$550. Thus

$$\text{Defender's adverse minimum} = \$2{,}100$$

While the defender shows an inferiority gradient of \$155 a year (1,550 ÷ 10), this seems to the analyst rather low as a projection for the challenger. Using \$200, he solves for the adverse minimum as follows:

$$\sqrt{2 \times 16{,}000 \times 200} + \frac{.10(16{,}000) - 200}{2} = \$3{,}230$$

Here the challenger's adverse minimum is so far above the defender's there is no need to pursue the inquiry further.[1] Replacement appears clearly premature.

[1] If the case were close it might of course be worth while to explore the possibility that with future salvage values taken into account the challenger's adverse minimum might be considerably below the figure developed here by the no-salvage formula.

5. GEAR-TOOTH BURRING MACHINE

We turn now to a somewhat different case, which involves the mechanization of a hand operation. The methods department of an industrial equipment manufacturer is asked to make a study of the purchase of a machine for burring gear teeth, the object being to eliminate filing by hand, presently required on a large percentage of the gears produced. The installed cost of such a machine is $11,350, complete with attachments and tooling.

On the basis of an anticipated production of 16,000 gears per year, divided by estimate among various sizes and types, the annual direct-labor saving is computed for each classification, the total for the several classes being $3,650. Current annual maintenance on the machine is estimated at $100, property taxes and insurance at $150. The next-year operational comparison is as follows, the defender in this case being the present hand-finishing setup:

	Next-year operating advantage	
	Challenger	Defender
Direct labor	$3,650	
Maintenance	.....	$100
Taxes and insurance	.....	150
Total	$3,650	$250
Net challenger advantage (defender inferiority)		$3,400

Since the defending setup has no salvage value, hence no capital cost,

$$\text{Defender's adverse minimum} = \$3{,}400$$

As it is impracticable in this case to project an inferiority gradient for the challenger by reference to the history of the defender, the analyst derives the challenger's adverse minimum by the service-life approach, using our short-cut formula, $c\left(\frac{2n-1}{n^2}+\frac{i}{1.4}\right)$. Since the new machine is expected

to be in use less than 1,000 hours per year, with wear and tear (though not, of course, obsolescence) reduced accordingly, he is willing to give it a prospective life of 12 years. This yields the following calculation:

$$11{,}350\left(\frac{23}{12^2} + \frac{.10}{1.4}\right) = \$2{,}624$$

Here the replacement of the hand process by the machine is overwhelmingly indicated, despite the omission from the reckoning of certain advantages not reduced to quantitative estimates. Thus the machine-finished gears are superior in workmanship and appearance to those hand-filed. There are other gains from the mechanization that would deserve attention in a close case but which in a one-sided contest like this are pure bonus.

6. TOOLROOM TEMPERING FURNACE

In this case we have another variation, the partial replacement of an existing facility. A machine shop has to rely on a production furnace for the tempering of tool room parts. These come in small batches, in sporadic fashion, and interfere with the regular work of the furnace. It is proposed to buy a small toolroom-type furnace to get rid of these interruptions and to effect other economies. The installed cost is $1,880.

A careful study of present practice indicates substantial loss of time in the toolroom from waiting to sandwich toolroom work into the schedule of the production furnace. On the other hand, there is a comparable loss of time in the production department due to the interruptions occasioned by toolroom work. The total labor saving from the proposed furnace is estimated, therefore, at about $350 a year. To this must be added a considerable saving in power, since the production furnace is rated 39 kilowatts, against 12 kilowatts for the toolroom unit. This saving is evaluated at $150 annually. With minor items added, the operational comparison appears,

therefore, as follows, the defender being, again, the existing setup.

	Next-year operating advantage	
	Challenger	Defender
Direct labor	$350	
Power	150	
Maintenance	....	$50
Floor space	....	10
Taxes and insurance	....	20
Total	$500	$80
Net challenger advantage (defender inferiority)		$420

Since the acquisition of the new furnace does not involve the disposal of the existing unit, which will continue in production work, no saving of present capital cost is in sight. It follows that only the operational inferiority of the present setup enters the reckoning. Hence

$$\text{Defender's adverse minimum} = \$420$$

Here again the challenger's inferiority gradient can hardly be estimated satisfactorily from the history of the defender; hence the service-life approach is indicated. Using a life of 15 years, the analyst obtains the following:

$$1{,}880\left(\frac{29}{15^2} + \frac{.10}{1.4}\right) = \$377$$

With a defender's adverse minimum of $420 and a challenger's minimum of $377, the acquisition is clearly indicated.

7. MULTIPLE-SPINDLE AUTOMATIC

A manufacturer of stainless-steel valves for the chemical industry is debating the replacement of a battery of 5 turret lathes, now 10 years of age, by one new multiple-spindle automatic costing $23,000. Because of the multiplicity of the operations to be performed (69 different jobs are in regular production on the present lathes) a tremendous amount of

new tooling will be required if the automatic is installed, the estimated cost of this tooling being $19,000. The old lathes can be sold at about $1,500 apiece, for a total recovery of $7,500.

A careful study of setup and cutting times on a representative sample of operations indicates that the automatic can do the work of the present turret lathes with a saving of the full time of four operators, plus one-fourth of the time of one setup man and one inspector, the annual value of this saving (including the saving of fringe benefits) being $17,800. The company is willing to set a value of $500 per year on the superior quality and finish of the work done on the automatic, and $300 on the saving in stock. Annual tooling costs, which are substantial because of frequent changes in product design, in addition to normal wear and breakage, it estimates to be lower by $1,750 on the automatic. The saving in maintenance is placed at $300. With other items the operational analysis works out thus:

	Next-year operating advantage	
	Challenger	Defender
Direct labor	$17,800	
Indirect labor	250	
Quality and finish	500	
Materials	300	
Tooling costs (normal)	1,750	
Maintenance	300	
Floor space	150	
Taxes and insurance	....	$300
Total	$21,050	$300
Net challenger advantage (defender inferiority)		$20,750

The old lathes, now salable for about $7,500 in all, will be worth an estimated $6,000 a year hence, making their next-year capital cost $1,500 plus $750 in interest. Accordingly

$$\text{Defender's adverse minimum} = \$23{,}000$$

As indicated, the new machine costs \$23,000, with \$19,000 additional for a full complement of tools. Against this \$19,000 there is a credit, however, arising from the fact that all the tools are new simultaneously, hence that the saving in tool-replacement costs will be higher for a year or two than the estimated normal saving of \$1,750 shown above in the operational comparison. This excess over the normal saving is estimated at \$4,500 for the first year and \$2,000 for the second. Deducting the combined present worths of these amounts (\$5,730) from the tooling cost of \$19,000, the analyst has \$13,270.[1] Added to the cost of the machine itself, this gives \$36,270. With the prospective service life estimated at 10 years, the challenger's adverse minimum is, therefore, as follows:

$$36{,}270\left(\frac{19}{10^2}+\frac{.10}{1.4}\right) = \$9{,}482$$

The replacement appears long overdue without regard to the untabulated advantages.

8. WATER-SOFTENING EQUIPMENT

A company supplying a domestic water-softening service is considering the replacement of its present stock of mineral with a new mineral having more than twice the capacity per cubic foot, and of which it will require, therefore, only half as much. The replacement will involve also the substitution of spun nylon bags for the cotton bags now in use. To supply the 4,100 tanks the company is now servicing will cost \$49,200 for mineral and \$8,200 for bags, making a total outlay of \$57,400. The resale value of the old mineral and bags is \$15,700.

Since the new mineral is only half as bulky (for the same

[1] The reader will recall our earlier admonition (p. 87) that the operational analysis should be based on a representative comparison of challenger and defender, excluding eccentricities or abnormalities peculiar to next year. In the present case the defender's prospective next-year inferiority in respect of tooling costs is far greater (\$6,250 versus \$1,750) than the average annual inferiority for a longer period of time; hence, to take the actual rather than the normal differential would make its total next-year inferiority unrepresentative. It is better to subtract the present worth of the abnormal defender inferiority from the cost of the new tooling.

capacity) as the old, it is estimated that the trucks which service the softener installations can increase the number of stops per day by 30 per cent. With a present cost of 28 cents per stop and with 129,000 stops per year, this represents a saving of about $8,300 annually. It is estimated further that the annual cost of regenerating the mineral will be reduced by $3,000. Moreover, because the new mineral requires only half as many bags, there is a prospective saving in bag repairs and replacements, estimated at $2,000 a year. On the other hand, there is an allowance of $1,000 yearly for additional mineral loss, and of $300 for increased taxes and insurance. Thus the picture shapes up as follows:

	Next-year operating advantage	
	Challenger	Defender
Labor and trucking	$ 8,300	
Regeneration	3,000	
Bag repair and replacement	2,000	
Mineral loss	....	$1,000
Taxes and insurance	....	300
Total	$13,300	$1,300
Net challenger advantage (defender inferiority)		$12,000

Because the present mineral will decrease rapidly in value as the new type becomes more generally used—and the old cotton bags, likewise—it is estimated that next year will see a decline of $5,000 from the present salvage value of $15,700. With interest of $1,570, this gives a next-year capital cost of $6,570, which combines with the operating inferiority of $12,000 to give

Defender's adverse minimum = $18,570

Since the mineral can be regenerated indefinitely, and since the replacement of worn-out bags is taken care of as a recurrent expense in the operational comparison, the life of the installation may be considered to be limited by obsolesence

only. Here the best estimate is 12 years. The challenger's adverse minimum is, accordingly:

$$57{,}400\left(\frac{23}{12^2}+\frac{.10}{1.4}\right) = \$13{,}261$$

The replacement is signaled by so wide a margin that it is unnecessary to explore the possibility that the challenger's adverse minimum would be even lower if reckoned with its future salvage values regarded. It is unnecessary, for the same reason, to consider advantages from the replacement not covered by the specific estimates.

9. PASSENGER AUTOMOBILE

A salesman is wondering whether to trade in his 2-year-old car on a new one costing $1,950. He is offered $950 for the old vehicle. Without the trade-in he confronts substantial repairs, including a new set of tires, a motor overhaul, and other items adding to about $250, which he believes will keep the car in service for another 18 months with only current maintenance.

It goes without saying that he prefers a new car, for reasons of prestige and for greater reliability, but the largest amount he is willing to pay for these benefits is $150 for next year. He estimates, further, that even after the overhaul the old car is likely to stand him considerably more in repairs than the new one, the difference being placed at $75. Thus the operating comparison lines up as follows:

	Next-year operating advantage	
	Challenger	Defender
Quality of service	$150	
Maintenance[a]	75	
Taxes	....	$10
Total	$225	$10
Net challenger advantage (defender inferiority)		$215

[a] Exclusive of the $250 overhaul, which is treated as a capital addition.

The present trade-in value of the old car is \$950, but it is believed that 18 months hence it will be down to around \$600. The next-year loss of salvage is, therefore, put at \$230 (two-thirds of \$350). Since the overhaul, costing \$250, will be good for 18 months, the analyst allocates two-thirds of that also, or \$170, to next year. With interest of \$130 on the overhaul and the present salvage value, it all adds up to a next-year capital cost of \$520.[1] With the operating inferiority of \$215, this gives

$$\text{Defender's adverse minimum} = \$735$$

The new car, which costs \$1,950, is expected to require a \$250 overhaul at the end of 2 years and again at the end of 3.5 years. This suggests the desirability of trying the adverse annual averages for these periods, for which terminal salvage values are estimated at \$950 and \$600 respectively. The inferiority gradient is taken from the old car, \$110 a year (215 ÷ 2).

2 Years

$$\frac{110 \times 1}{2} + \frac{1950 - 950}{2} + \frac{.10(1950 + 950)}{2} = \$700$$

3.5 Years

$$\frac{110 \times 2.5}{2} + \frac{1950 - 600}{3.5} + \frac{.10(1950 + 600)}{2} = \$651$$

Average capital additions, \$250 ÷ 3.5 . . . . = 71

Total . . . . = \$722

The 2-year period of service appears to yield the adverse minimum, which is \$700. This compares with \$745 obtainable with the old car from 18 months of further service. Replacement seems indicated, but by a narrow margin.

[1] As we explained earlier, this method of handling capital additions is simpler than the theoretically more correct procedure of figuring the defender's adverse average for the period over which the additions, if made, will presumably extend the service life. The latter procedure requires an estimate of the defender's inferiority gradient over this period. Suppose in the present case the analyst projects the past gradient (215 ÷ 2) over the next 18 months, applying our general formula for the adverse average, as modified for a defender (page 122). He comes out with the following:

$$215 + \frac{110 \times .5}{2} + \frac{1{,}200 - 600}{1.5} + \frac{.10(1{,}200 - 600)}{2} = \$733$$

The difference between the two procedures as applied here is negligible.

II. Replacement and Expansion

We turn now to a group of cases which involve both replacement and expansion.

10. COAL CUTTER

A coal mine presently using a 25-year-old short-wall cutter is contemplating the installation of a modern cutter equipped with a "bugduster," at a cost of $8,300. The old unit can be disposed of for about $1,000.

The new cutter is much faster than the old one and makes possible a considerably increased production. The net value of this increased output, after allowing for the cost (other than cutting) of getting it out, is placed at $4,000 a year. Not only is the output greater; there is a saving of direct labor on the cutting operation itself amounting to $3,000 a year, plus $500 in indirect labor. With minor items added, the operational comparison comes out thus:

	Next-year operating advantage	
	Challenger	Defender
Net value of increased output	$4,000	
Direct labor	3,000	
Indirect labor	500	
Maintenance	300	
Taxes and insurance	.....	$100
Total	$7,800	$100
Net challenger advantage (defender inferiority)		$7,700

Although the old cutter is now salable for $1,000, a rapid softening in the secondhand market is anticipated. Allowing for a runoff of $500 next year, with interest of $100 on the present value, the analyst obtains a capital cost of $600. Added to the $7,700 just shown, this yields

$$\text{Defender's adverse minimum} = \$8,300$$

With an estimate of 12 years for the challenger's service life,

its adverse minimum works out thus:

$$8{,}300\left(\frac{23}{12^2} + \frac{.10}{1.4}\right) = \$1{,}919$$

Obviously, the replacement is urgent.

11. JIG-BORING MACHINES

The precision-boring department of a metalworking establishment has among its machines three 21-year-old units which no longer have the required accuracy. It is proposed to sell one of them for $500, to transfer one to a different department where the requirements are less exacting, to retain one in a stand-by capacity in its present department, and to purchase three new jig-boring machines, one small, one medium, and one large, at a total cost of $33,000.

It is estimated that because of increased spindle speeds and other improvements the new machine will reduce boring time by 20 per cent as compared with the old units they replace. This effects a direct-labor saving of $2,950 per year. Not only will the work be done faster, it will be done more accurately, with a saving in the subsequent operations of inspection, machining, and assembly estimated at $4,800 a year. Moreover, the added capacity provided by the new machines will eliminate the necessity for subcontracting jig work. The potential saving from this elimination is, conservatively, $4,500 annually. Thus, with minor items added, we have the following operating analysis:

	Next-year operating advantage	
	Challenger	Defender
Direct labor, precision-boring operation	$ 2,950	
Direct labor, subsequent operations	4,800	
Saving from elimination of subcontracting	4,500	
Maintenance	400	
Taxes and insurance	....	$350
Total	$12,650	$350
Net challenger advantage (defender inferiority)		$12,300

When the analyst comes to reckoning the next-year capital cost of the three old machines, he confronts the fact that one of them is to be transferred to another department of the same enterprise and one retained for stand-by service. He confronts the necessity, therefore, of estimating their conversion values. Since the transferred machine in the department of destination will save an estimated $1,800 a year through the reduction of outside subcontracting now being let by that department, its conversion value is obviously higher than the $500 it would bring in the secondhand market. But since this value cannot be above the cost of buying an equivalent machine in that market, a cost estimated by the analyst at not over $1,000, the latter figure is taken for the purpose. This figure is used also for the machine retained as stand-by. With the $500 disposal value of the third machine, the combined salvage value is, therefore, $2,500. Taking interest on this sum, $250, and estimating the next-year runoff in salvage value at $500, the analyst comes out with a defender capital cost of $750. Added to the operating inferiority of $10,300, this gives

$$\text{Defender's adverse minimum} = \$11{,}050$$

Since a large element ($4,500) of the defender's next-year operating inferiority consists of inadequacy and since the analyst is unwilling in this instance to forecast a comparable accumulation of inadequacy by the challenger, he rejects the defender's gradient of $490 a year ($10,300 ÷ 21) as a projection for the latter. Instead, he prefers to assume a 15-year service life and solve for the adverse minimum by our alternative formula:

$$33{,}000\left(\frac{29}{15^2} + \frac{.10}{1.4}\right) = \$6{,}610$$

This adverse minimum implies a gradient of about $440 a year (6,610 ÷ 15), somewhat lower than the defender's $490 gradient but acceptable to the analyst, all things considered. Replacement is indicated, obviously, by a wide margin.

12. HYDRAULIC PRESS

A manufacturer of conveying and power transmission equipment is contemplating the acquisition of a new 400-ton hydraulic press with an installed cost of $28,760, to replace three smaller presses of advanced age (51, 39, and 31 years). The old machines are salable for a total of $1,100.

The new press will have the capacity to blank the ends of chain links ⅝ inch and ¾ inch thick now camographed and ground in the steel shop or sawed and milled in the machine shop. It will also make it possible to offset cold in the chain department many links now offset hot in the steel shop. The concentration of this work in the chain department will effect a considerable saving in transportation and materials handling and permit far better control of production. Moreover, the substitution of one press for three in the chain department will release floor space for piling finished side bars near the new unit. The annual saving from reduced materials handling, better production control, and increased floor space is estimated at $1,500. The saving from cold offsetting is placed at $400.

It is planned to make the tooling of the new unit interchangeable with that of a 500-ton press now in use in the chain department and adjacent in location. This standardization of tooling, coupled with a saving in setup time as compared with the old presses it is proposed to retire, yields an estimated yearly saving of $2,250. Moreover, the new press will make possible the combination of certain operations now done separately, such as cutting off and stamping, or piercing pitch holes and piercing attachment holes. The annual saving from doubling up these operations is placed at $1,850.

There is another advantage from the proposed replacement. By working the new press two shifts, it will be possible to relieve the present 500-ton press of a good deal of the lighter work that now occupies it, releasing at least 1500 hours a year of its time for heavy work on products other than chain presently being flame-cut elsewhere. The saving

from this source will be in the vicinity of $3,000 yearly. Finally, it is estimated that the new press will yield an annual saving in maintenance over the three old ones of $2,400 and that its greater reliability and reduced risk of shutdowns is worth $400. Thus we have

	Next-year operating advantage	
	Challenger	Defender
Materials handling and floor space	$ 1,500	
Cold offsetting	400	
Tooling and setup time	2,250	
Combined operations	1,850	
Released time of other equipment	3,000	
Maintenance	2,400	
Risk of outage	400	
Taxes and insurance	......	$350
Total	$11,800	$350
Net challenger advantage (defender inferiority)		$11,450

The resale value of the old presses is almost negligible, $1,100; hence their capital cost is negligible also. Allowing $200 for next-year loss of salvage and $100 for interest:

$$\text{Defender's adverse minimum} = \$11{,}750$$

The new press is given a service life of 18 years. Its adverse minimum is, therefore

$$28{,}760\left(\frac{35}{18^2} + \frac{.10}{1.4}\right) = \$5{,}160$$

With a figure less than half the defender's adverse minimum, replacement appears urgent.

13. PLASTIC PREFORM PRESS AND PREHEATER

A manufacturer of molded plastic parts is considering the purchase of a plastic preform press and a preheater at a total cost of $15,350, to replace the present combination of an 18-year-old press and a 4-year-old preheater, for which a

trade-in allowance of $1,400 is offered. If the old press is continued in operation, it will require renewals costing $1,000, which, however, should keep it running with only current repairs for at least 5 years.

The proposed press and preheater have a much greater capacity than the present combination and will permit the application of preforming and preheating to practically all the current production for which this technique is suitable, the increase in this application being estimated at 247,000 parts a year. It is estimated further that the use of preforms in connection with preheating shortens the subsequent molding operation 10 per cent as to loading time and 15 per cent as to curing time, with an over-all saving of about 14 per cent. This shortening of the molding time yields a direct labor saving estimated at $13,950 a year. In addition, there is expected to be a saving of $350 a year from greater efficiency in the pressing and preheating operation itself, and a saving of $250 in maintenance. The operational comparison, therefore, lines up as follows:

	Next-year operating advantage	
	Challenger	Defender
Labor in the molding operation	$13,950	
Labor in the pressing and preheating operation	350	
Maintenance	250	
Taxes and insurance	......	$150
Total	$14,550	$150
Net defender operating inferiority		$14,400

It is estimated that the present salvage (trade-in) value of the old units, $1,400, will decline $200 next year. To this is added an allocation of $200 to next year from the $1,000 required for renewals to keep the old press in service (these renewals being good for 5 years) and $240 in interest, making

a total next-year defender capital cost of \$640.[1] With the operating inferiority of \$14,400, this gives

$$\text{Defender's adverse minimum} = \$15{,}040$$

Since the defender's operational inferiority is largely inadequacy and since the analyst does not care to predict a similar history for the new equipment, he approaches the challenger's adverse minimum by a service-life estimate. The press he is willing to give 15 years; the preheater, 10 years. Taking 12 years as a middle estimate, he has

$$15{,}350\left(\frac{23}{12^2} + \frac{.10}{1.4}\right) = \$3{,}548$$

Obviously, the replacement is mandatory.

14. FARM TRACTOR

A farmer with a 7-year-old tractor confronts the problem of paying out \$300 for a major overhaul and keeping it 5 more years (until the next major overhaul) or trading it in on a new and somewhat larger one costing \$1,750. The trade-in value is \$450.

When he attempts to cast up the next-year operational comparison between the two machines, he is in some difficulty because of the multiplicity and diversity of the operations which they must power. He has records of past repair costs and fuel consumption on the existing unit, however, and knows the number of hours run in a typical year. Moreover, he recalls in a general way the frequency and duration of shutdowns due to mechanical failure of the old unit and the inconvenience and loss resulting. After careful consideration, he places the annual saving in maintenance at \$50 and the saving in fuel and lubricants at \$30. The increased reliability of the new tractor, with the reduced risk of shutdowns at crucial periods, he puts at \$50. For the increased

[1] This treatment of capital additions to the defender, it will be recalled, is a short cut usable when the amount involved is relatively small or when added refinement would make no difference to the result. See above, p. 123.

capacity he is willing to pay $75 a year. Thus he comes up with the following analysis:

	Next-year operating advantage	
	Challenger	Defender
Maintenance[a]	$ 50	
Fuel and lubricants	30	
Risk of outage	50	
Value of additional capacity	75	
Taxes	....	$10
Total	$205	$10
Net challenger advantage (defender inferiority)		$195

[a] Exclusive of the $300 overhaul, which is treated as a capital addition.

Since the old tractor, if worth keeping at all, will probably be worth keeping 5 more years (to spread the overhaul expense), the analyst proceeds to compute its adverse average for that period, using our general formula for the adverse average, as adapted to a defender:[1]

$$\text{Next-year operating inferiority} + \frac{g(n-1)}{2} + \frac{c-s}{n} + \frac{i(c+s)}{2}$$

when g is the inferiority gradient, n the number of years of further service, c the present capital cost (salvage value plus the cost of the overhaul), s salvage value at the end of the contemplated period, and i the interest rate, in decimals. Estimating the terminal salvage value at $200 and the gradient for the next 5 years at $25 a year,[2] he has

$$195 + \frac{25 \times 4}{2} + \frac{750 - 200}{5} + \frac{.10(750 + 200)}{2} = \$403$$

This adverse average for the 5-year period may be taken as equivalent to the adverse minimum of the old tractor.

It is believed that the new tractor, like the old one, will require a major overhaul, costing, say, $300, about the end

[1] Above, p. 122.

[2] This gradient estimate is obtained simply by projecting into the future the defender's past rate of inferiority accumulation (195 ÷ 7).

of its seventh and twelfth years; hence it seems probable that its adverse minimum will be associated with one or the other of those periods of service. Solving for the adverse minimum for the shorter period, the analyst obtains by our no-salvage formula

$$1{,}750\left(\frac{13}{7^2}+\frac{.10}{1.4}\right)=\$589$$

Clearly the replacement cannot be justified on the basis of a 7-year life, at least with future salvage value disregarded. The next move is to try for 12 years:

$$1{,}750\left(\frac{23}{12^2}+\frac{.10}{1.4}\right)=\$405$$

Here the case appears close if the analyst ignores both the cost of rebuilding ($300) at the end of the seventh year and the salvage value at the end of the twelfth year. Since the cost of the overhaul will at least equal terminal salvage value and is earlier in time, it is evident that this figure of $405 is, if anything, on the low side of the adverse minimum and that the replacement will have to be justified, if at all, by considerations outside the tabulation.

15. BENDING MACHINE

The next case presents a straight expansion problem. A manufacturer of garage doors is investigating the desirability of buying equipment to bend the overhead track radius for these doors, which he now purchases already bent. A power bender, together with the necessary bending jigs, costs approximately $15,000.

At present the company pays 11 cents each to have its track bent outside, with a total cost per year of $4,700. It is estimated that the total cost of doing it inside, inclusive of overhead but exclusive of capital costs on the proposed equipment, will be 4.3 cents per track, or a total of $1,840 per year. The operational comparison is, therefore

	Next-year operating advantage	
	Challenger	Defender
Excess of outside cost over inside cost	$2,860	
Net challenger advantage (defender inferiority)		$2,860

Since the acquisition of the new machine permits no saving of existing capital cost, we have, obviously,

$$\text{Defender's adverse minimum} = \$2{,}860$$

The bending machine is given a 12-year life by the analyst; hence, its adverse minimum is

$$15{,}000\left(\frac{23}{12^2} + \frac{.10}{1.4}\right) = \$3{,}467$$

On this showing, it will pay to continue the subcontracting.

Obviously it is possible to multiply examples indefinitely, but these will have to suffice for our present purpose. While they do not cover all the problems and situations confronted in practice, the possible variations being almost infinite, they do illustrate the application of our procedure over a sufficient range to permit the analyst to make his own adaptations. In so doing he will find considerable scope for his ingenuity.

Chapter X

THE INTEREST CHARGE FOR REPLACEMENT PURPOSES

Up to now we have been using an arbitrary interest rate of 10 per cent for illustrative purposes, with the promise of a later discussion of the criteria and considerations by which an appropriate rate can be selected. To this discussion we turn in the present chapter.

We devoted some space at an earlier stage of this study (page 43) to the reasons why interest must be used in replacement analysis, and it is unnecessary to review the argument here. It is important to reemphasize, however, that interest works both forwards and backwards. It is not only an increment to past magnitudes; it is a discount from future magnitudes. For this reason it is insufficient merely to charge interest on the investment in a proposed machine (or on the salvage value of an existing one); we must also discount the future operating inferiorities which we are commensurating with capital cost in the replacement analysis. Everything involved in the comparison of mechanical alternatives must be brought to a common time reference by means of the interest rate.

PROFIT FROM REPLACEMENT

Let us begin with a necessary distinction between profit for accounting and for replacement purposes. As we pointed out in Chap. III (page 39) the accountant is essentially retrospective, being concerned primarily with the recording and measuring of *past* operations. From his standpoint it may be quite legitimate to consider as profit on past investment any return whatever above zero. Once the money has

been sunk, even a small return is better than none. In apprais- ing the advantages of *future* investment, however, this measure- ment is inappropriate. It is not sufficient that such investment promise merely a return above zero; it must return more than the cost of money if the commitment is to be worth while. To find out whether it will yield such a return it is necessary that the cost of money itself be used as the interest rate for the calculation.

The point has been discussed as follows by an eminent authority on equipment policy.

> The practical answer to the question, "Why recognize interest in connection with engineering economy studies?," may be briefly stated as follows: Interest exists as a business fact; if you borrow money it is necessary to pay interest; if you have money you can get interest for it. Where a choice is to be made between alternatives which involve different money receipts and disbursements at different times, it is therefore essential to consider interest. Engineer- ing economy studies generally involve decisions between such alternatives.[1]

It is one thing to recognize interest, or the time cost of money, but another to measure it. Here we must distinguish between the cost of new money brought into an enterprise from the outside and the cost of using the company's own funds. Suppose we consider first the case of outside financing.

EXTERNAL FUNDS

When money is obtained by borrowing, the charge is contractual and definite. When it comes from equity financ- ing, however, its cost may be at best a matter of estimate. There is a further complication (in the United States) arising from the difference in the tax status of interest and of equity earnings. It is appropriate, therefore, to consider these two types of outside financing separately.

BORROWED MONEY. It may seem at first glance that the cost of borrowed money is identical with the contractual interest rate, plus amortization of discount and expenses, if any,

[1] Eugene L. Grant, *Principles of Engineering Economy*, rev. ed., p. 71, The Ronald Press Company, New York, 1938.

incident to obtaining the funds. For certain purposes, this conception may be quite satisfactory, but not for replacement analysis.

Borrowed capital increases the risk of the equity capital in every case and in some cases may even jeopardize the solvency of the business. The guarantee of security for the lender is necessarily an impairment of the security of the borrower. There is thus a hidden price for such capital in reduced safety, and prudent management will take it into account. The real cost of borrowed money may therefore be well above its nominal cost; by how much, each enterprise must decide for itself. It is this adjusted cost in any case that should be used in replacement analysis.

We can offer no general rule for the evaluation of the added risk from borrowing. It depends, naturally, on the character of the business concerned, on the existing capital structure, the terms of the available loan, and many other factors. Certainly when this added risk is allowed for, there can properly be wide differences in the interest rates used for replacement analysis, even when the nominal cost of borrowed capital is the same.

EQUITY MONEY. What is the cost of new equity money? From the standpoint of the *existing* owners of an enterprise—and it is their interest exclusively that controls the decision to raise new capital—it is *the future earnings the new equity holders will claim.* If the new money adds more to the earnings of the enterprise than its contributors can claim as their share, the excess goes to the insiders.

Let us illustrate. A company is formed by the sale of 100,000 shares at \$100 each, giving it an invested capital of \$10,000,000. On this capital it develops an earning power (after taxes) of 20 per cent annually, or \$20 a share. The directors believe that the investment can be doubled and still continue to earn 20 per cent overall. But since the market capitalizes the present earnings on a 10 to 1 basis, the shares selling for \$200 each, it is necessary to issue only 50,000

additional shares to achieve this expansion. If the additional capital pays off as expected, it will increase the annual earnings of the enterprise to $4,000,000. Of this the holders of the original 100,000 shares will take two-thirds, or $2,666,667, while the holders of the 50,000 shares of new stock will take $1,333,333.

Since the new stock claims a share of $1,333,333 in the annual earnings and yields $10,000,000 of additional capital to the company, should we conclude that the cost of the money is 13.3 per cent? *It is so if the enterprise pans out as indicated.* Unlike bond interest, which is fixed by contract regardless of earnings, the claim of additional common equity capital depends on the subsequent success of the undertaking to which it contributes.[1] The greater this success, the greater the claim and the greater, therefore, the cost of equity as against loan capital. Thus if the earnings of our hypothetical enterprise are $6,000,000 a year after the expansion, rather than $4,000,000, the new stock will claim $2,000,000; hence the cost of the added capital will be 20 per cent. On the other hand, if these earnings are $3,000,000, the cost is 10 per cent. Finally, if there are no future earnings, the cost is nil.

THE TAX ANGLE

There is more to the problem than this, however, for there is the tax angle to be considered. We said nothing about it in connection with the cost of borrowed money because interest paid on debt is tax deductible. Being deductible, its cost to the borrower is unaffected by the tax.[2] In the case of equity financing, however, it is necessary to distinguish between incorporated and unincorporated enterprises.

[1] Preferred stock dividends present an intermediate case which it is not necessary to discuss separately.

[2] If the taxpayer's income before interest is less than the interest itself, he has no tax liability and is quite obviously unaffected by the tax. If this income exceeds interest, he can offset an amount equal thereto, leaving the balance after interest (but before income tax) the same as it would be in the absence of the tax. What the tax does in this case is to absorb part of the earnings above the cost of money without changing that cost itself.

If an individual businessman, *A*, obtains new equity money by selling a participation in his enterprise to a partner, *B*, the latter's share in the earnings is not a part of *A*'s income, hence is not taxable to *A*. But if a corporation sells a block of stock to *B*, the share of this new stock in the common earnings is taxable to the corporation. If *B* buys this stock for 10 times its prospective annual earnings *after taxes* and if his expectations prove correct, the claim of his stock *before taxes* (assuming the present Federal corporate rate of 38 per cent) will be about 16 per cent on his capital contribution.[1] It is this percentage, not the 10 per cent that *B* receives, that represents the cost of the money to the corporation. This is the figure that must be compared with the cost of borrowed capital, discussed above.

We spoke earlier of the premium that must be added to the interest rate on loan capital to allow for the added risk to the equity, and of the limit which this risk imposes on debt financing. There may be practical limits also to the expansion of equity capital by new stock flotations, even when these promise a profit for existing stockholders over and above the cost of the funds thus obtained. If a preferred issue, the new stock may operate like borrowing, though in lesser degree, to increase the risk of the common equity. Or if the issue is common, it may result in a change in the control of the enterprise to the disadvantage of present holders. For these and other reasons the real cost of outside money may be higher than it appears.

INTERNAL FUNDS

We turn now to the cost of money when the enterprise is using its own funds. The authority previously cited discusses the question as follows:

> Where ownership funds are available without borrowing it is not necessary to pay out interest to any creditor. Nevertheless interest is a cost just as much as if it had to be paid out. There is

[1] $\frac{10}{100 - 38} = .161$

always the alternative of lending money at interest (or perhaps paying off a debt on which interest is being paid) or somehow investing funds productively so as to yield a return. If the opportunity does not exist for the private corporation or governmental body it does exist for the stockholder or the citizen who pays the taxes. Thus, in this situation, interest is a cost in the sense of an opportunity foregone, an economic sacrifice of a possible income that might have been obtained by investment elsewhere. . . . Where ownership funds are to be used to finance plant investments, the prospective return should compare favorably with returns obtainable from the investment of capital at like risk. Here the returns commonly received from capital investment in industry are relevant.[1]

Here we have again the idea of "opportunity cost," presented earlier in the present study in the discussion of the cost of continuing ownership of an asset already held (Chap. III). According to the authority quoted, the rate of interest charged against replacement investment financed by the company's own funds should reflect the return on the best alternative investment of comparable risk, this being the measure of opportunity.

However simple opportunity cost may be in theory, it is not easy to derive in practice. The return from alternative investment of like hazard cannot be precisely determined; at best the analyst can only define a reasonable range within which it can be presumed to fall.[2] It follows that the figure actually chosen must be at best a very rough estimate.

It is necessary to add in this connection that the return on alternative outside investment is a proper measure of opportunity cost *only when it has the same tax status in the hands of the recipient as his own internal funds*. If the owner of an unincorporated enterprise is in the 80 per cent income-tax bracket, the taxable equivalent of a 2 per cent tax-exempt investment is 10 per cent. He cannot afford to invest in his own business for less. Or if a corporation subject to a 38 per cent rate can invest in other corporations to earn 10 per cent per annum

[1] Eugene L. Grant, *op. cit.*, pp. 72, 79.

[2] The alternative must be not only of like hazard, it may be subject to certain requirements as to liquidity.

tax-free (to itself), it cannot afford internal investment for less than 16 per cent.[1] When the opportunity cost of internal funds is derived by comparison with a tax-free alternative, it must be the *taxable equivalent* of the return on this alternative.

THE RATE IN PRACTICE

As a theoretical proposition, the interest rate for replacement purposes should not be *below* the return obtainable on outside investment of comparable risk and tax status nor *above* the cost of bringing outside money into the business.[2] Which of these limits prevails depends on the circumstances of the case. The return obtainable from outside investment should govern when the enterprise has a sufficient supply of funds to take advantage of all internal investment opportunities that promise to be profitable at an interest rate (cost of money) equal to or higher than that return. In this case the company is able to saturate its internal investment from its own resources, hence is on a surplus, or overflow, basis as to capital. On the other hand, the cost of obtaining outside money should govern when the internal resources are insufficient for such a saturation and when the company is, accordingly, on a capital deficit basis. In this event investment should be saturated to the cost of outside funds.[3]

This, we said, is the theoretical proposition. As a practical matter, it is impossible to resurvey the applicable cost of money every time a replacement analysis is made, and those companies which use an interest rate in their analyses (as we shall see later, many do not) usually select a standard or

[1] Under present law this figure would be about 15 per cent, since only 85 per cent of intercorporate dividends are exempt.

[2] This assumes that the real cost of getting outside money is higher than the return obtainable from comparable outside investment. If it is lower, the interest rate may be above it, since in theory the enterprise cannot properly charge for replacement purposes less than it can get from outside investment.

[3] Since the cost of bringing outside money into the business may be considerably above the return obtainable from the outside investment of surplus internal funds, there may be a zone of interest rates within which the company may be said to be on neither a surplus nor a deficit basis. Within this zone it should saturate its investment to the lowest rate made possible by its available funds.

conventional rate for application to all replacements, subject, of course, to change at relatively infrequent intervals. What this rate should be depends, of course, on the circumstances. These vary so widely, no general prescription is possible; each enterprise must make its own appraisal.

LOADING THE RATE

We suggested earlier that when the increased risk for the equity capital is taken into account the real cost of borrowing may be higher than the nominal interest rate. We suggested also that there may be in some cases disadvantages to new equity financing that are not reflected in the apparent cost, such as dilution of control, etc. These considerations may justify a certain amount of "loading" of the nominal cost of *outside* money. This loading should be applied with discrimination, however, as the circumstances of the particular enterprise justify. It is not a surcharge to be added on general principles.

There is another type of loading advocated by some writers, namely, an arbitrary, blanket addition to the cost of money to introduce a "safety factor" into the replacement analysis. Consider, for example, the following:

> This margin of safety may be introduced into economy studies in several ways, one of which is the interest rate or required rate of return. Sometimes this is established as a matter of corporate policy. For instance, one oil company made a general requirement that no plant investment would receive budgetary approval unless it effected savings which would show a prospective return of 20 per cent. A manufacturing enterprise with an average cost of capital of 7 per cent used an interest rate of double that figure, that is 14 per cent, in its economy studies. One public utility paying about 5 per cent for borrowed funds made all of its economy studies on an annual cost basis, using interest at 7 per cent.[1]

If this type of indiscriminate loading results in the use of an interest rate higher than justified on the grounds discussed earlier, it can in no way enhance the "safety" of the enterprise. For as we shall see in a moment, the use of such a rate

[1] Eugene L. Grant, *op. cit.*, p. 80.

protects the defending asset beyond the economical point of replacement and results in a consequent loss. True, if other elements of the replacement analysis happen to be biased toward premature replacement, the opposite bias from the use of an excessive interest rate may be advantageous, but on the other hand if these elements yield a retarded replacement, the two errors are compounded. Since the error in the other factors is presumably random, or unsystematic (given a correct method of analysis), the loading of the interest rate is an attempt to cure an unknown bias with one that is known. This simply introduces a systematic bias into the combined result. How can an enterprise enhance its "safety" by a procedure *certain* to yield a relative loss *if the replacement analysis is otherwise correct?* It is loading the dice against itself.

EFFECT OF DIFFERENCES IN THE RATE

While the interest rate for replacement purposes should reflect as nearly as possible the applicable cost of money, it can vary within a moderate range without too drastic an effect on the result. We can illustrate by reference once more to the hypothetical challenger presented earlier in Table 1 (page 78). In the Table on page 169, the case has been refigured at various interest rates ranging from 0 to 20 per cent, thus disclosing the differences attributable to these variations.

Suppose we consider the range between 5 and 15 per cent as the one within which the interest rate for replacement purposes may reasonably fall. Reckoned at one limit of the range, 5 per cent, the adverse minimum of this challenger is \$1,053; reckoned at the other limit, 15 per cent, it is \$1,310. The extreme difference is therefore \$257. Measured from the adverse minimum of \$1,173 at 10 per cent interest, the mid-point of the range, the deviations are \$120 and \$137, respectively.

While these variances in the challenger's adverse minimum are by no means negligible, neither are they intolerably large. An interest rate of 15 per cent, yielding an adverse minimum of \$1,310, will protect a defender with an inferiority gradient

TABLE 7

ADVERSE MINIMUM, AT VARIOUS RATES OF INTEREST, OF A CHALLENGER HAVING A COST OF $5,000 AND AN INFERIORITY GRADIENT OF $100 A YEAR, WITH NO CAPITAL ADDITIONS AND NO SALVAGE VALUE

Year of service	Uniform annual equivalent of capital cost and operating inferiority for period ending with year indicated and for interest rate indicated				
	0 per cent	5 per cent	10 per cent	15 per cent	20 per cent
	1	2	3	4	5
1	$5,000	$5,250	$5,500	$5,750	$6,000
2	2,550	2,738	2,929	3,122	3,318
3	1,767	1,933	2,104	2,281	2,462
4	1,400	1,554	1,716	1,884	2,059
5	1,200	1,345	1,500	1,664	1,836
6	1,083	1,221	1,371	1,531	1,701
7	1,014	1,145	1,289	1,447	1,616
8	975	1,098	1,238	1,392	1,561
9	956	1,071	1,205	1,357	1,524
10	950*	1,057	1,186	1,335	1,500
11	955	1,053*	1,176	1,321	1,484
12	967	1,056	1,173*	1,313	1,475
13	985	1,064	1,174	1,310*	1,469
14	1,007	1,076	1,178	1,310*	1,466
15	1,033	1,091	1,185	1,312	1,465*
16	1,063	1,109	1,194	1,315	1,466
17	1,094	1,128	1,204	1,319	1,467
18	1,128	1,148	1,215	1,325	1,469
19	1,163	1,169	1,226	1,330	1,471
20	1,200	1,191	1,238	1,335	1,473

of $100 a year about two and a half years longer than a rate of 5 per cent, which yields a challenger's minimum of $1,053. But this is a 10-point difference in rates. A 5-point difference would shift the replacement signal for such a defender by less than a year and a half, or by something like 10 to 12 per cent of its normal service life.[1]

[1] If the challenger's adverse minimum is $1,053 (as figured at 5 per cent) the defender becomes replaceable at the end of its eleventh year. With a minimum of $1,173 (as figured at 10 per cent) it is replaceable at the end of 12 years. Both these calculations assume that replacement is considered only at the end of each year. For convenience, we assume no salvage value and no capital additions.

If we had to deal only with interest rates between 5 and 15 per cent, we would be fortunate indeed. As we shall show later, however, it is not uncommon for replacement analyses to be made by formulas or rules of thumb which imply interest rates of 40 or 50 per cent. But this is not all. Even when they are not retarded by the use of such devices, replacements are often delayed by lack of capital (or for other reasons) to a point where they can *stand* an interest rate of 40 or 50 per cent and still be advantageous.

While the difference in the adverse minimum reckoned on a 10 per cent and a 15 per cent basis may be relatively small, the difference between the 10 per cent and the 50 per cent reckonings is enormous. We can illustrate again by the hypothetical challenger of Table 7.

Interest Rate Used, Per Cent	*Adverse Minimum*
0	$ 950
5	1,053
10	1,173
15	1,310
20	1,465
30	1,831
40	2,250
50	2,704

The adverse minimum of $2,704 obtained with a 50 per cent interest rate will protect a defender with an inferiority gradient of $100 a year for 28 years, 16 years beyond its proper point of retirement when the challenger's minimum is reckoned on a 10 per cent basis.[1]

LOSS FROM RETARDED REPLACEMENT

It is obvious that a very high interest rate is a formidable barrier to remechanization. The excessive adverse minimum it gives the challenger protects the defender far beyond the time when it would be replaceable if a lower rate were used in the analysis. If money is obtainable at the lower rate, this overprotection results in an avoidable loss equal to the amount by which the defender's operating inferiority (and

[1] Assuming again that the defender has no salvage value or capital additions.

capital cost, if any) during the period of overretention exceeds the challenger's adverse minimum properly computed.

We pointed out a moment ago that the use of a 50 per cent interest rate for the challenger in Table 7 yields an adverse minimum of $2,704 as against $1,173 with a 10 per cent rate, and that the former would protect a defender with a $100 inferiority gradient (and no capital cost) for 16 years longer than the latter. What is the loss from such overprotection? During the 16-year period this defender would accumulate an excess inferiority over and above the challenger's correct adverse minimum ($1,173) totaling $12,000.[1] The present worth of this excess *at the beginning of the period* would be $4,342.[2] Here is the loss from delayed replacement, viewed from that point of time, a very substantial loss indeed considering that the cost of the challenger is only $5,000.

This is an extreme case perhaps, but even a 30 per cent interest rate yields a substantially excessive adverse minimum for our hypothetical challenger (assuming still that the cost of money is 10 per cent). The excess of $658 ($1,831 − $1,173) would protect a defender with a $100 gradient 6 to 7 years too long and generate an accumulated loss of $2,100 during the interval, the present worth of which at the beginning of the period would be $1,276.[3] In either case we are dealing with sizable losses as compared with the results of a correct replacement policy.

If the use of too high an interest rate can develop losses on one side, it follows, of course, that the use of too low a rate can develop them on the other. Such losses are likely to be much the smaller, however, since the possible downward deviations from the cost of money are necessarily narrower than the possible upward deviations. To cite our hypothetical challenger once more, the use of zero interest when the cost of money is 10 per cent results in an adverse minimum too

[1] Assuming the first year of this period to be neutral, with zero excess inferiority.

[2] At 10 per cent discount.

[3] Taking the 7-year period and assuming zero excess inferiority the first year.

low by \$223 (\$1,173 − \$950). This results in a replacement premature by 2 years (assuming again a defender with a \$100 gradient), occasioning a loss equal to the amount by which the defender's inferiority would have been below \$1,173 *had it been kept in service for the additional time*. This loss is comparatively insignificant in relation to those generated by the upward deviations in interest rates just considered.

UNDERSATURATION OF REPLACEMENT

The only thing that can possibly justify a company in using such astronomical interest rates as 30 to 50 per cent in its replacement analyses *either explicitly or implicitly*, is an acute shortage of capital that cannot be replenished with outside money on tolerable terms. In that case it must ration among the available replacement opportunities whatever internal funds it happens to have. Whether this rationing is accomplished by raising the stated interest rate used in replacement analyses or by some other method is immaterial; the implicit rate goes up if not the explicit.

If the cost of additional money is 50 per cent and if its own funds are insufficient to saturate its replacements to a lower interest rate, an enterprise may properly charge this rate in its analyses. But if it can get money for less (after due allowance for added risk and other adverse features of outside financing discussed earlier) it should do so and saturate its replacements to the cost of the money, whatever it may be.

Many enterprises are reluctant to engage in outside financing for replacement purposes and tend therefore to get along on their own resources, save in situations of exceptional urgency. If these resources are inadequate, they may live indefinitely in a condition of chronic undersaturation. The disposition to restrict replacements to the available internal funds is clearly indicated by the replies to an inquiry on replacement practice conducted by the Institute a few years ago. We quote a few excerpts from our investigator's report.

When funds are not available for replacement, the action taken depends on the urgency of the situation. If replacement is urgent they obtain outside capital, though the policy preferably followed is to make replacements only as reserves are available. If reserves at any time are not sufficient the replacement is necessarily delayed.

The plant engineer is limited to a certain yearly budget which he cannot exceed, even though he may be convinced of the economies of further replacements.

They frequently come across cases where the customer desires a new machine but does not have the ready cash to purchase it, and therefore the old unit is operated until such time as the replacement can be made.

He reports that it is quite common for the customers to delay replacement because funds are not available.

Failure to make replacements as soon as justified at an interest charge equal to the cost of the necessary money can result only in a loss of profit otherwise obtainable, the measure of the loss being the excess operating inferiority and capital cost of all equipment kept beyond its proper service life.[1] This loss can be serious, or even fatal. In such cases additional money may be the price of survival.

RETURN ON NET WORTH AS A MEASURE OF THE COST OF MONEY

Occasionally one encounters the view that the interest rate for replacement purposes should coincide with the average rate of return on net worth for the enterprise concerned.

The reasoning underlying this view may be formulated as follows: "If the enterprise is able to earn say 20 per cent on net worth, it cannot afford to put money in replacement equipment unless it will return at least this much. By imposing an interest charge of 20 per cent, the replacement analyst sees to it that additional investment is as profitable as the existing investment. Thus he protects the enterprise against a shrinkage in its over-all rate of return."

This argument propounds a common fallacy we expect

[1] Excess of current operating inferiority and capital cost of the incumbent machines over the adverse minima of their respective challengers, computed at an interest rate equaling the cost of money.

to discuss at length later, in Chap. XIII, and we shall deal with it here only briefly. Let us begin by asking a pertinent (or impertinent) question. Why be satisfied with a 20 per cent return on the investment in the challenger? Why not defer replacement in all cases until this investment yields 50, or even 100 per cent? For if the over-all profit rate of the enterprise can be maintained by waiting for a 20 per cent return, why not *increase* it by waiting for something higher?

But this is not all. We find implicit in the rate-on-net-worth criterion the paradoxical, or at least anomalous, conclusion that a successful enterprise should keep its equipment longer than an unsuccessful one. For since the interest requirement on the challenger investment is a hurdle, or barrier, to replacement, if we tie this requirement to the profit rate we obtain automatically an inverse relation between profitability and mechanization. Consistent application of the rate-on-net-worth standard would therefore equip a highly profitable operation with mechanical antiques, while tooling a losing undertaking with the latest and best.

This criterion of the interest charge on replacement investment leads obviously to theoretical and practical absurdities. There is in fact no relation between the appropriate charge and the return on net worth. The test of replaceability, as we have seen, is whether the new equipment will yield a balance of advantage after allowance for the cost of the money involved. If there is such a balance, the replacement should be made regardless of whether the enterprise is operating overall at a profit or a loss.[1] (A reduction of loss is obviously quite as valuable as an increase in profit of like amount.)

So long as new facilities yield an advantage over and above the cost of money, the excess augments the return on the *existing* equity, whatever that return may be.[2] The notion

[1] Assuming, of course, that it intends to remain in business.

[2] This is true even though the rate of return on net worth *inclusive of new equity created in financing the facilities* may be reduced in the process. The object of the existing owners of an enterprise is the expansion of the *amount* of their own profit, not the maintenance of the present *rate* of return on total equity including capital subsequently brought in. This expansion goes on so long as additional replacements return anything over the cost of the additional capital.

that this return (especially if high) should be used in lieu of the cost of money reflects the basic illusion that by deferring replacement until it can stand a high interest rate we obtain a "profit" or "return" at the same rate. This is probably the most stubborn and persistent illusion to be found in the literature of replacement policy. If a replacement will stand an interest charge in excess of the cost of money, this is evidence that it is overdue, hence evidence of *loss*, rather than profit, from the delay. The greater the excess charge it will stand, the greater this loss. We repeat, *the interest rate that maximizes profit is the cost of money.* Any deviation therefrom, whether up or down, will produce a *relative* loss.

The main result of this lengthy discussion is reassuring. While the cost of money may be difficult to determine with precision, especially the opportunity cost of internal funds, an exact determination is not essential to the selection of the interest rate for replacement analyses. Limited deviations of this rate from the cost of money (say up to 5 per centage points either way) have only a moderate effect on the timing of the replacement signal, *provided* the analysis is otherwise correct. There is no objection, therefore, to a reasonable range of variation in the interest rate employed in replacement studies. Rather than strive for exactitude on this point, we can better devote our efforts to seeing to it that the procedure is "otherwise correct."

Chapter XI

THE ORTHODOX ENGINEERING FORMULA—MINIMUM AVERAGE COST

Having expounded a novel procedure for replacement analysis, we propose now to employ it as a standard for testing some of the more common formulas and devices in current use.

However varied the dodges, short cuts, and rules of thumb it may approve for "practical" replacement analysis, the engineering profession is in substantial agreement on the general theoretical formula: minimum average cost. We may properly describe this formula as the "orthodox," or "classical," prescription of the profession. It embodies an approach so basic, indeed, that most, if not all, of the alternatives thus far advanced in engineering literature can be classed as variants or derivatives of it.[1] For this reason it deserves the most careful scrutiny.

[1] This is not true of certain highly theoretical formulas developed by mathematicians and appearing outside engineering literature, as the reader can ascertain, if he desires, by an examination of the following contributions:

Hotelling, Harold, "A General Mathematical Theory of Depreciation," *Journal of the American Statistical Association*, Vol. 20, p. 340 (1925).

Preinreich, G. A. D., "The Theory of Depreciation," *Econometrica*, Vol. 6, p. 210 (1938).

Idem, "The Practice of Depreciation," *Econometrica*, Vol. 7, p. 235 (1939).

Idem, "The Economic Life of Industrial Equipment," *Econometrica*, Vol. 8, p. 12 (1940).

These authors do not make the mistake of dealing in cost comparisons only, as do the proponents of minimum average cost. They deal rather with the concept of "net rental." A machine is replaceable when its net rental is extinguished. Unfortunately, they fail to translate this concept into practically measurable magnitudes. Their speculations remain, therefore, on a completely abstract and academic basis, and are of interest only to mathematical theorists.

WHAT IS IT?

According to the more sophisticated statements of the formula, a facility is replaceable when the lowest combined annual average of operating cost and capital cost obtainable from the challenger is less than the corresponding average obtainable hereafter from the defender, both averages being time-adjusted.[1]

We can illustrate by an example. The following table derives minimum average cost for a hypothetical challenger.

TABLE 8

DERIVATION OF MINIMUM AVERAGE COST OF A CHALLENGER COSTING $5,000, WITH FUTURE OPERATING COSTS AS INDICATED, ASSUMING NO CAPITAL ADDITIONS AND NO SALVAGE VALUE, INTEREST BEING 10 PER CENT[a]

Year of service	Operating cost for year indicated	Time-adjusted annual average for period ending with year indicated		
		Operating cost	Capital cost	Both combined
	1	2	3	4
1	$3,000	$3,000	$5,500	$8,500
2	3,100	3,048	2,881	5,929
3	3,200	3,094	2,011	5,104
4	3,300	3,138	1,577	4,716
5	3,400	3,181	1,319	4,500
6	3,500	3,222	1,148	4,371
7	3,600	3,262	1,027	4,289
8	3,700	3,300	937	4,238
9	3,800	3,337	868	4,205
10	3,900	3,373	814	4,186
11	4,000	3,406	770	4,176
12	4,100	3,439	734	4,173*
13	4,200	3,470	704	4,174
14	4,300	3,500	679	4,178
15	4,400	3,528	657	4,185

[a] Figures do not always add because of rounding.

This challenger's minimum average cost is $4,173, for a 12-year service life. The replacement signal comes, of course,

[1] See Eugene L. Grant, *op. cit.*, Chap. 14.

when the defender shows a minimum average in excess of this figure.[1]

As a rule, the defender's next-year cost is considered to be its minimum, the assumption being that by the time it is old enough to be up for replacement analysis its operating cost is likely to be rising faster than its capital cost (if any) is declining.[2] If this is so, the combination of the two costs for next year is necessarily lower than their annual average for any longer period. When this assumption is employed, the replacement analysis consists simply of comparing the defender's next-year cost with the challenger's minimum life average as developed in the table.

CONVERSION TO GAP-AND-GRADIENT BASIS

While the minimum-average-cost formula is usually presented as a comparison of the lowest *total* costs of challenger and defender, it can readily be converted to the gap-and-gradient basis made familiar by the presentation of our own formula. Such a conversion is desirable to facilitate a comparison of the two procedures. It is accomplished simply by subtracting from the operating costs of both challenger and defender an amount equal to the challenger's first-year operating cost, in this case $3,000. So converted, the analysis for the challenger in Table 8 is shown on the next page.

With this conversion the table appears more familiar. Instead of the challenger's future operating costs in full, we have in Col. 1 the *excess* of these costs over the first-year level. We have, in other words, an inferiority gap built up by a cost increase (gradient) of $100 a year, the width of the gap being the *difference* between the current and the original

[1] As we saw earlier (Chap. 5), the timing of replacement can be determined from a comparison of the defender and the present challenger only when the character of future challengers is fixed by assumption. This is as true of the minimum-average-cost formula as of any other. In this case the assumption that rationalizes the formula is that future challengers will have the same minimum average cost as the present one. Under no other supposition can the replacement signal be timed as indicated above. In this connection the reader may refer again to p. 64.

[2] We have discussed this simplifying assumption elsewhere (p. 85).

cost. Stated otherwise, it is the difference between the current cost and that obtainable from a new replica of the same machine.[1]

TABLE 9

TABLE 8 CONVERTED TO GAP-AND-GRADIENT BASIS[a]

Year of service	Excess of operating cost for year indicated over first-year cost	Time-adjusted annual average for period ending with year indicated		
		Excess of operating cost	Capital cost	Both combined
	1	2	3	4
1	$ 0	$ 0	$5,500	$5,500
2	100	48	2,881	2,929
3	200	94	2,011	2,104
4	300	138	1,577	1,716
5	400	181	1,319	1,500
6	500	222	1,148	1,371
7	600	262	1,027	1,289
8	700	300	937	1,238
9	800	337	868	1,205
10	900	373	814	1,186
11	1,000	406	770	1,176
12	1,100	439	734	1,173*
13	1,200	470	704	1,174
14	1,300	500	679	1,178
15	1,400	528	657	1,185

[a] Figures do not always add because of rounding.

Since we have subtracted $3,000 from Col. 1, we of course get an adverse minimum lower by that amount than the minimum average cost of $4,173 in Table 8, but since we also subtract $3,000 from the defender's next-year operating cost, the comparison of the two machines is unaffected. We now have for the defender's adverse minimum the amount by which its next-year operating cost *exceeds* the challenger's (the challenger's next-year cost saving) plus its capital cost,

[1] The cost of a new replica need not coincide with the original cost on the same machine if there have been changes in price levels in the meantime. The formula normally assumes stability in this respect, hence the gap can be described either way.

if any. In other words, we have its operating-cost *inferiority* relative to the challenger, plus capital cost.

It may appear at first glance that the adverse minima of challenger and defender derived from this conversion of the minimum-average-cost procedure are identical with those yielded by our own method. A closer look will dispel this illusion, however. Let us consider the difference between the two formulas with respect to (1) the challenger's adverse minimum, (2) the defender's adverse minimum.

DIFFERENCE WITH RESPECT TO THE CHALLENGER'S ADVERSE MINIMUM

In our formula, as applied to the challenger, the inferiority gap is measured by the adverse difference between the operating performance of the facility for any given year (taking into account the difference in both operating cost and revenue) and *the performance of the best alternative then available*, usually an improved facility. In the minimum-average-cost formula, it is the adverse difference between operating *cost* in the given year and *operating cost on the same facility new* (first-year cost). Stated otherwise, our gap reflects the inferiority of operating performance, comprehensively considered, relative to the current challenger, while the other reflects the inferiority in one element of performance only, operating cost, as compared with the original cost on the same unit. The one measures from a moving target; the other from a fixed target.

Since the minimum-average-cost formula takes cognizance only of the increase in the challenger's own operating cost, without regard to the character of the current alternatives, it must be obvious that *it ignores challenger obsolescence entirely.* But this is not all; it ignores also those forms of challenger service deterioration not reflected in operating cost, that is to say, those which affect the revenue, rather than the expenditures, of the enterprise.

Since the object of replacement policy is to minimize the sum of capital cost and *total* operating inferiority and since from the standpoint of this policy one type of inferiority is

TABLE 10

ADVERSE MINIMUM OF CHALLENGER IN TABLE 9, DERIVED (1) BY THE MINIMUM-AVERAGE-COST METHOD, (2) BY OUR METHOD[a]

	Minimum-average cost				Our method			
		Time-adjusted annual average for period ending with year indicated				Time-adjusted annual average for period ending with year indicated		
Year of service	Excess of operating cost for year over first-year cost	Excess of operating cost	Capital cost	Both combined	Operating inferiority for year (including obsolescence)	Operating inferiority	Capital cost	Both combined
	1	2	3	4	5	6	7	8
1	$ 0	$ 0	$5,500	$5,500	$ 0	$ 0	$5,500	$5,500
2	100	48	2,881	2,929	200	96	2,881	2,977
3	200	94	2,011	2,104	400	188	2,011	2,199
4	300	138	1,577	1,716	600	276	1,577	1,853
5	400	181	1,319	1,500	800	362	1,319	1,681
6	500	222	1,148	1,371	1,000	444	1,148	1,592
7	600	262	1,027	1,289	1,200	524	1,027	1,551
8	700	300	937	1,238	1,400	600	937	1,537*
9	800	337	868	1,205	1,600	674	868	1,542
10	900	373	814	1,186	1,800	746	814	1,560
11	1,000	406	770	1,176	2,000	812	770	1,582
12	1,100	439	734	1,173*	2,200	878	734	1,612
13	1,200	470	704	1,174	2,400	940	704	1,644
14	1,300	500	679	1,178	2,600	1,000	679	1,679
15	1,400	528	657	1,185	2,800	1,056	657	1,713

[a] Computed with interest at 10 per cent. Figures do not always add because of rounding.

as bad, dollar for dollar, as any other, it must be evident that a formula which takes cognizance of only one type can give results wide of the mark. To illustrate, let us suppose that the hypothetical challenger in Table 9 is subject not only to a prospective increase of $100 a year in operating costs but also to an obsolescence of the same amount.[1] Table 10, on the preceding page, compares the derivation of the adverse minimum by the two formulas.

Here is an interesting picture. Under the minimum-average-cost formula this hypothetical challenger is given an adverse minimum of $1,173 (Col. 4) as against $1,537 (Col. 8) when obsolescence is taken into account. Moreover, its indicated service life is 12 years as compared with 8 years by our method.

Obviously the difference between the two results is even greater if we assume that obsolescence accounts for two-thirds or some higher fraction of the total inferiority gradient. To take the extreme case, suppose that the $200-a-year gradient is entirely obsolescence (there being no rise in the challenger's own operating cost with age). What then is the adverse minimum under the minimum-average-cost formula? It becomes in this case the lowest obtainable time-adjusted annual average of capital cost alone, which is $500 a year for an infinite service life.[2] Unless the asset is brought to term, like the wonderful one-hoss shay, by irreparable physical collapse—a contingency not covered by the formula—it is presumed to be good forever.

This example suffices to establish the proposition that when the challenger is subject to obsolescence (or to deterioration of service not reflected in operating cost) the formula yields *too low* an adverse minimum and an excessive life expectancy. To correct these errors it is necessary to take cognizance of the challenger's operating inferiority from all

[1] This means that the first-year performance of the best current alternative to the challenger will improve $100 a year as compared with the original performance of the challenger itself, or of a new replica thereof.

[2] The $500 is interest (at 10 per cent) on $5,000, the assumed cost of the asset.

causes, not simply from a cost standpoint, and, more important still, to measure this inferiority from the performance of the best alternative available year after year, not from the original performance of the challenger itself.

DIFFERENCE WITH RESPECT TO THE DEFENDER'S ADVERSE MINIMUM

Since the minimum-average-cost formula deals only with comparative expenditures or disbursements, ignoring differences between mechanical alternatives that affect the revenue, rather than the outgo, of the enterprise, it follows that when applied according to its own logic it disregards all elements of the defender's next-year operational inferiority to the challenger not reflected in comparative operating costs. To this extent it tends to *understate* the defender's adverse minimum, hence to weight the replacement analysis in its favor.

While this is the logical result of an exclusive preoccupation with costs, it does not follow that it is always fully realized in practice. The analysis of the defender's next-year operating inferiority to the challenger, while supposedly confined to cost comparisons only, may take cognizance directly or indirectly of at least some of the difference in the value of the service rendered. There are frequently certain elements of variance in operating performance that can be treated either as cost differences or as differences in service value.[1] Moreover, other elements not properly classifiable as cost differences may be given some unspecified weight as "imponderables" or "irreducibles" of the analysis.

For this reason it seems likely that the deficiency in the defender's next-year operating inferiority resulting from the incomplete inclusion of service-value (revenue) differences is less, on the average, than the deficiency in the challenger's adverse minimum by reason of the disregard of obsolescence and noncost deterioration. In any event, the balance of the

[1] For example, loss of production time due to breakdowns may be evaluated as either an increase of cost or a loss of revenue.

two errors may fall either way in particular cases. The use of minimum average cost is like buying a pig in a poke.

MINIMUM AVERAGE COST IN PRACTICE

It is safe to say that the minimum-average-cost formula is seldom applied in the theoretically correct manner indicated in Table 8. Occasionally, no doubt, some replacement analyst with a yen for "highbrow" solutions attempts a computation of this character, but in general if the formula is used at all it is on a modified basis.

A correct application, it will be noted, requires year-by-year estimates of the challenger's future operating cost.[1] Once these estimates are made, together with the necessary estimates of capital cost, they permit the determination of the minimum average cost as in Table 8, and with it the best service life. This best service life is a by-product of the calculation; it does not need to be estimated in advance. In practice, however, the procedure is usually quite different. It begins with an estimate of the challenger's service life. Instead of the year-by-year projections of operating cost, there is a single estimate for the *average* cost over this estimated life. There is also the average capital cost for the same period, generally straight-line depreciation plus average interest. The two life averages are then combined to yield minimum average cost.[2]

If the service-life estimate used in this modified procedure happens to be close to the period that would be disclosed by a Table 8 analysis and if the estimated life average of operating cost is in harmony with the year-by-year projections called for by the correct method, the minimum average cost obtained in this manner may conform fairly well to the theoretical figure.[3] Otherwise it will not.

[1] Or, on the converted basis (Table 9), year-by-year estimates of *increases* in these costs over the first-year level.

[2] There are several versions of the modified procedure. The one here described is recommended in the leading text on replacement analysis, *Principles of Engineering Economy*, by Eugene L. Grant. See Chap. 15 of the revised edition.

[3] It will not conform exactly even if the estimates are correct because of faulty adjustment for the interest factor. As we pointed out previously (p. 93),

FLIGHT FROM THE FORMULA

Whatever the vagaries of the modified procedure just described, it is at least intended to yield an approximation to the result of the full procedure described in Table 8. This cannot be said, however, of a further modification, to which we now turn.

We cited earlier the failure of the minimum-average-cost analysis to take account of challenger obsolescence and the bias in the replacement analysis which results. This has worried the proponents of the method, apparently, for some of them have recommended an "allowance" or "adjustment" for this bias in cases where prospective obsolescence is substantial. This adjustment consists of substituting for the estimated service life of the challenger a purely arbitrary, or fiat, period only a fraction as long. Average cost computed for this truncated service life is, of course, higher—because of the spreading of capital cost over a short period—than the minimum average itself, thus supposedly compensating for the nonrecognition of obsolescence.

Eugene Grant comments, for example,

> In the manufacturing industries, where obsolescence of new equipment within a short time is a serious hazard, a capital recovery period for the economy study is often established as a matter of company policy, by a specification such as "No replacement will be made unless the machine will pay for itself in three years." If so, this should be the estimated life. Otherwise, it is simply a matter of a conservative forecast of life, based on all the relevant information available to the estimator.[1]

It is a fair question whether a resort to an arbitrarily shortened capital recovery period when challenger ob-

straight-line depreciation and average interest give too low a figure for average capital cost, while a simple average of future operating costs (if these are rising) gives too high a result. The two errors, being opposite, tend to offset each other, but they do so imperfectly.

[1] *Principles of Engineering Economy*, rev. ed., p. 203. This procedure seems to be approved by engineers rather generally, including such outstanding authorities on replacement policy as Paul T. Norton, Jr. See his study, "The Selection and Replacement of Manufacturing Equipment," *Bulletin of the Virginia Polytechnic Institute*, 1934.

solescence is in prospect does not constitute, as to such cases, a complete abandonment of the minimum-average-cost formula. We believe it does. The assumed period no longer has any relation to the service life that would yield the lowest average cost; it is, on the contrary, a shot in the dark, informed by no rational guide or standard that we can discover, save possibly some vague hunch as to the probable rapidity of obsolescence in the case. This substitute for minimum average cost is so popular, however, and so widely used, that it deserves close study, which we propose to give it in the next chapter.

Chapter XII

THE SHORT PAY-OFF REQUIREMENT

We are concerned in this chapter with what is undoubtedly the most popular replacement device in use, the short pay-off requirement. This imposes on the challenger an arbitrary "capital recovery" period during which the investment must be recouped from "cost savings."

We spoke in the preceding chapter of the resort to abbreviated capital recovery periods by some of the proponents of the minimum-average-cost formula in an effort to compensate for the failure of that formula to take account of future obsolescence. We do not mean to imply, however, that the short pay-off requirement originated in this way. As we shall see shortly, it was apparently in use as a rule-of-thumb device long before the engineering profession conferred on it a measure of respectability as a modified version of minimum average cost. It is, indeed, a part of our industrial folklore.

I. Nature and Prevalence of the Device

In practice, the short pay-off is computed in a great variety of ways. It would be difficult, indeed, to think of any method, however illogical or even preposterous, that has not somewhere been tried. We have made no attempt to compile a complete catalog of these variants, which would be as tedious as it is unnecessary, but we have discussed a few of them on page 269 for the benefit of the curious.[1] We shall consider here only the most popular versions of the device.

[1] It is suggested that the text of this chapter be read before p. 269.

When an industrial executive states that he requires replacements to "pay for themselves" in 2 years, the chances are he means that the estimated annual "cost saving" of the challenger over the defender must equal one-half of the investment involved in the replacement, or, in other words, that it must equal straight-line depreciation on the investment applied over a 2-year period. If the defender has no appreciable salvage value, this investment is of course the full cost of the challenger; if it has such value, the investment is usually reduced by that amount.

If this is *not* what is meant by a 2-year pay-off, the odds are that a more complicated procedure is used which adds a requirement for interest on the investment during the capital recovery period. Prevailingly this is interest on the full, or original, investment, not on the *average* outstanding over the period. Thus if the challenger costs $5,000 (over and above salvage, if any, on the defender) and if interest is set at 10 per cent per annum, the annual cost saving necessary to permit replacement is $3,000, as compared with $2,500 under the simpler no-interest calculation.

As a rule, the reckoning of annual cost saving is based on a comparison of the estimated performance of the challenger and the defender *for next year*, assuming some "normal" rate of utilization. In some cases, however, the saving is computed from estimates of the *average* performance of both over the pay-off period, while it is derived in others from a comparison of the challenger's average for that period with the defender's performance for next year only. Since these more elaborate forms appear to be used rather infrequently, we shall assume in the following discussion that annual cost saving, for the purpose of the short pay-off calculation, is the difference between next year's operating costs on both sides.

Since we are primarily interested in the short pay-off as generally applied in industry, we shall relegate to the Appendix any consideration of the more elaborate forms and concentrate on the popular versions just described.[1] How prev-

[1] See p. 269.

alent is the device? And what is the relative frequency of various pay-off periods?

FREQUENCY OF VARIOUS PAY-OFF PERIODS

So far as we are aware, no general survey has ever been made to determine the proportion of replacement decisions in American industry that are simply "hunched," without benefit of formula or rule of thumb, but there can be no doubt that when the analysis goes beyond mere intuition and relies on some test of replaceability, the test is likely to be the recovery of the investment over a specified pay-off period. As we indicated earlier, this is unquestionably the king of all "practical" short cuts.

While we have no trustworthy statistical evidence on the prevalence of the device itself, we do have a few surveys indicating the frequency of various pay-off, or capital recovery, periods when it is used. Almost universally, this period is only a small fraction of the challenger's normal service life. Thus a machine with anticipated service life of 15 years, which is set up for depreciation in the books of the purchaser on that basis, is required to "pay for itself" in 2 or 3 years.

Pay-off period required, years	Per cent of companies reporting	
	National Bureau[a]	Manufacturing Industries[b]
1 or less	5	5
1.5 and 2	38	38
2.5 and 3	20	21
3.5 and 4	13	13
4.5 and 5	21	21
Over 5	3	3

[a] National Bureau of Economic Research, *Recent Economic Changes*, Part 1, p. 139. The questionnaire was distributed by the Bureau in a study for the Committee on Recent Economic Changes of the President's Conference on Unemployment.

[b] *Manufacturing Industries*, Vol. XV, No. 1, p. 27. Percentages do not add to 100 because of rounding.

The preference for very brief periods is clearly indicated by two questionnaire surveys made in the late twenties, both,

unfortunately, limited to manufacturers only. The results of these surveys, one by the National Bureau of Economic Research, covering 200 companies, the other by *Manufacturing Industries*, covering 39 companies, are presented in tabular form on page 189.

These tabulations suggest that, in manufacturing at least, a 2-year pay-off period is the most frequent, with 3 years and 5 years about even for second place.[1] Both surveys are agreed in showing that periods of 3 years or less comprise roughly two-thirds of the cases.

It is interesting to note that in addition to these 39 companies reporting fixed pay-off periods 37 "had no definitely established period wherein new equipment is required to pay for itself," while 12 reported "varying periods depending on the particular kind of equipment involved." Whether this proportion of 37 with no periods to 51 using them is representative of manufacturing generally, it is impossible to say.

Even when "fixed" periods were reported, there were some qualifications expressed. In the words of the article presenting the results, "There are 39 which have definitely fixed the time in which equipment must earn its way. True, some of these give a little leeway; they may say, for example, '2 or 3 years,' but generally speaking they confine themselves to a fairly closely restricted range. . . . The indications are that about one-half of those who set periods consider them somewhat flexible. In other words, they do not lean over backwards for the sake of living up to a rule."

The statistical findings are supported in general by the results of another survey, made in the late thirties, based this time on personal interviews with manufacturing executives. The impressions of the investigator are reported as follows:

> The most usual requirement was for return of investment in three years or less, and a one-year interval was not unusual. . . . The longer intervals were more likely to be tolerated for heavy

[1] The almost exact agreement of these two independently conducted surveys, one with a total of only 39 cases, must be put down as a statistical accident. The samples cannot be that good. Even a less complete concurrence would suffice for our present purpose, however.

equipment. In some industries such as textiles, baking, and packing, technological change seemed to provide relatively few changes that would return capital in less than three or four years, so that firms that believed in modern equipment would frequently have to accept a 20 or 15 per cent return on the investment. A good many of the companies required a higher rate of return in poor years than in good ones, in spite of the fact that frequently this percentage return was calculated at current volume.[1]

We come now to a more recent survey, made by the Machinery Institute in 1948. The following tabulation reflects the replies of 51 member companies to the question: "What pay-off period do your customers typically require on the investment in a replacement machine?"

Pay-off Period, Years	*Per Cent of Replies*
1	14
2	41
3	19
4	8
5	8
Over 5	10
	100

Here again we have two-thirds or more of the cases falling in the 3-years-and-under classification.[2]

Another recent survey comes out with a somewhat different picture. The tabulation below summarizes the replies of 560 companies using machine tools, the question being "If you would replace existing machine tools before they are actually worn out physically, how much savings in per cent of cost of new machine tools would have to be shown to induce their purchase?"[3] We have converted the percentages into pay-off periods.

[1] Ruth P. Mack, *The Flow of Business Funds and Consumer Purchasing Power*, p. 255, Columbia University Press, New York, 1941.

[2] It may be added, as an interesting sidelight, that a somewhat larger number of MAPI member companies, responding to a question on their own pay-off requirements (as distinguished from those of their customers) showed a good majority with periods *over* 3 years. The reasons for the disparity between the two distributions are not clear at this writing.

[3] Survey by *Iron Age*, reported in the issue of Sept. 11, 1947.

Payo-ff Period, Years	*Per Cent of Replies*
1	4
2	13
3	23
4	22
5	24
Over 5	14
	100

This survey shows a higher proportion of relatively long pay-off periods (over 3 years) than the other studies reviewed above—higher, obviously, than the general experience of machinery salesmen indicates. This may reflect the fact that the question asked is hypothetical, or the fact that it was asked in inverted form, calling for required percentages of savings to cost rather than for required ratios of cost to savings (pay-off periods). Perhaps both factors figured in the result.

While these surveys are not wholly consistent, and while they leave much to be desired for other reasons (for instance, they are limited primarily to manufacturing equipment), the general outlines of the picture are confirmed every day by the less formal but no less weighty observation of machinery salesmen. The testimony here is conclusive. Without marshaling an array of witnesses, we shall content ourselves with one recent statement that happens to have come to our attention, that of a machine-tool builder: "In normal times it is virtually impossible to sell a new machine tool unless you can prove to the customer that it will pay for itself in less than three years."[1]

It is obvious that American industry, in so far as it applies any mathematical test to replacement decisions, is overwhelmingly addicted to the requirement that the challenger "pay for itself" in a small fraction of its service life. How did this curious practice develop?

HISTORY OF THE DEVICE

The historical record on the evolution of the short pay-off is fragmentary indeed, but such as it is, it suggests that 100

[1] Joseph L. Trecker, "The Economic Justification for Investment in Plant Assets." (An address before the Production Conference of the American Management Association, Chicago, Nov. 14, 1946.)

years ago the periods allowed were prevailingly much longer than now. We have one opinion, for example, dating from 1832:

> Engines for producing power, such as wind-mills, water-mills, and steam-engines, usually last a long time. But machinery for producing any commodity in great demand seldom actually wears out; new improvements, by which the same operations can be executed either more quickly or better, generally superseding it long before that period arrives: indeed, to make such an improved machine profitable, it is usually reckoned that in five years it ought to have paid for itself, and in ten to be superseded by a better.[1]

If this observer judged rightly that in his day manufacturing equipment was bought generally on a 5-year pay-off and kept in service for 10 years, he was describing a state of affairs vastly superior to our own. It is interesting to note that his judgment as to the prevailing American practice coincided closely with that of two observers of the English scene. While these commentators do not refer specificially to the pay-off period in England, they estimate an average service life for industrial equipment that appears incompatible with the very short pay-offs now in vogue in the United States. The first is Karl Marx, who wrote in the 1860's that "One may assume that the life-cycle, in the essential branches of great industry, now averages ten years."[2] The other is Friedrich Engels, himself a textile manufacturer in England, who estimated this average, in 1858, at 10 to 13 years.[3]

These bits of evidence are obviously too fragmentary to support any firm conclusions. Part of the difference between the (apparent) 10-year life expectancy of manufacturing machinery in the middle of the nineteenth century and the present average of around 20 years may be due to the greater physical durability of modern equipment, though this factor

[1] Charles Babbage, *On the Economy of Machinery and Manufacturers*, Chap. XXVII, Philadelphia, 1832.

[2] *Capital*, Vol. II, p. 211, Untermann transl., Charles H. Kerr & Company, Chicago, 1919.

[3] This range was cited in correspondence with Marx. *Der Briefwechsel zwischen Friedrich Engels und Karl Marx 1844–1883*, Zweiter Band, pp. 252*ff*., herausgegeben von A. Bebel und Ed. Bernstein, Stuttgart, 1913.

should be offset, in part at least, by what is commonly supposed to be a greater rate of obsolescence in recent times. At most we have here only an interesting speculation.

Whether or not the prevailing pay-off period demanded of manufacturing equipment was 5 years a century ago, as Babbage believed, the question remains how it got so fantastically short as the 1, 2, or 3 years so frequently required today. One explanation that has come to our attention is both ingenious and plausible. Oddly enough, it lays the blame on the zeal of machinery salesmen. In an effort to overcome customer resistance, the theory runs, these salesmen have stressed time and again the shortness of the interval required for their products to "pay for themselves"—a year in one case, 6 months in another, 2 years in another, and so on. Naturally enough, the customers, assailed continually by such arguments, have at last adopted them as a standard and have come to demand as universally right and proper what the machinery salesmen, in their zeal for business, have offered only in particular instances.

Be this as it may, the fact remains that the short pay-offs currently demanded of replacement equipment result generally in an undue prolongation of the life of existing installations and a corresponding accumulation of mechanical zombies. The cost of this practice to American industry it is impossible to estimate satisfactorily, but it is possible to explore the subject further, which we shall now do.

II. Consequences of the Short Pay-off

We were talking recently with a distinguished European economist who expressed his admiration for the boldness and vigor with which American industrialists adopt new production techniques. "I understand," he said, "that they even require new machines to pay for themselves in two years." It came as a surprise, and something of a shock, when we pointed out that this practice, far from being, as he assumed, an evidence of dynamic progressiveness, is precisely the reverse. It betokens a stodgy conservatism, willing to protect

its aged mechanical assets by a Chinese wall. For the short pay-off requirement is a barrier of the most formidable character to the replacement of equipment.

There is no mystery about this proposition; on the contrary, it is completely obvious. The shorter the pay-off period required of the challenger, the larger the next-year advantage over the defender that is necessary for replacement, hence the longer the defender must be kept before this advantage appears. Thus if the investment in the challenger is $10,000, a 3-year pay-off (on the usual no-interest reckoning) awaits an annual advantage of $3,333; a 2-year pay-off awaits $5,000, while a 1-year pay-off must wait for $10,000. It may take years, even decades, for the advantage to rise from $3,333 to $10,000; in the meantime the defender lives on.

HYPOTHETICAL CASE

Obviously, the effects of the short pay-off requirement will differ from case to case, depending on the particular circumstances. For the purpose of general illustration, however, we can explore the consequences of the device as applied to a hypothetical example. To avoid conjuring up still another imaginary machine, suppose we revert once more to the challenger described in Table 1 (page 78).

The correct adverse minimum of this machine is $1,173. But what is the equivalent by the short pay-off method? Since the acquisition cost is $5,000, a 2-year period yields $2,500 while a 3-year period yields $1,667.[1] This is by the simple, or no-interest, version of the device. By the more complicated and less popular version which adds an interest charge, the corresponding figures, assuming a 10-per-cent rate, are $3,000 (2,500 + 500) and $2,167 (1,667 + 500).[2]

We come now to the real question. What is the loss from

[1] This assumes that the defender with which this challenger is compared has no remaining salvage value of consequence. As we indicated earlier, defender salvage is usually deducted from the cost of the challenger in deriving the investment to be spread over the pay-off period.

[2] As already indicated, when interest is added it is usually reckoned on the original cost of the machine.

the use of these high figures for the challenger's adverse average? As we pointed out a moment ago, they protect the defender beyond its proper service life. The resulting loss is the amount by which the defender's operating inferiority *during the period of overprotection* exceeds the challenger's correct adverse minimum of $1,173 a year.[1] We can illustrate by assuming a defender having an inferiority gradient of $100 a year during this period. The retardation of replacement and the consequent loss are shown below for each of the short pay-off calculations indicated a moment ago for the challenger.

Form of short pay-off	Challenger's adverse average resulting 1	Period of overprotection of defender, (years)[a] 2	Loss from overprotection[b] 3	Present worth of loss at beginning of period[c] 4
Without interest:				
2-year	$2,500	14	$9,100	$3,680
3-year	1,667	5	1,000	686
With interest:				
2-year	3,000	19	17,100	5,258
3-year	2,167	10	4,500	2,289

[a] The period is computed on the assumption that the defender's excess inferiority in the first year of overprotection is zero.

[b] Cumulative sum of excess inferiority during the period in Col. 3, assuming zero excess the first year and an increase in the excess thereafter at the rate of $100 a year.

[c] Loss indicated in Col. 4 discounted to beginning of period of overprotection at 10 per cent.

This is of course a purely fanciful case, but it shows how long the defender may be protected beyond its proper service life by a challenger's adverse average derived from a short pay-off calculation. It shows also how heavy may be the penalty for such overprotection. It indicates, finally, how wide may be the variation in the results of different pay-off periods and modes of reckoning. The choice between one period and

[1] This proposition supposes that the defender has no salvage value during the period of overprotection.

another is often made in the most casual manner, as though a year more or less made little difference. Yet the loss from a 2-year (no-interest) pay-off is more than five times the loss from the 3-year version. Obviously the length of the period is not a matter to be taken lightly.

EFFECT OF DEFENDER SALVAGE VALUE

The hypothetical case just presented assumes that the defender has no salvage value at the time it is challenged. Let us consider for a moment what happens when there is such value. As we said earlier, it is customary to subtract defender salvage from the gross cost of the challenger and to divide the net, or additional, investment by the pay-off period to get the challenger's adverse average.

The obvious effect of this subtraction is to reduce the adverse average by the proportion which the defender's salvage value bears to the challenger's cost. Thus if the former is \$1,000 and the latter \$5,000, the application of a 2-year pay-off to the net investment yields an average of \$2,000 instead of the \$2,500 obtained in the absence of defender salvage, while the 3-year pay-off yields \$1,333 against \$1,667. It may appear that in so far as this adjustment reduces the challenger's adverse average it mitigates the tendency of the short pay-off method to overprotect the defender. Before we reach this conclusion, however, we must consider the fact that this treatment of salvage value results in the exclusion of capital cost from the reckoning of the defender's own adverse magnitude, hence leaves this magnitude too low.[1] The reduction on the challenger's side of the comparison is thus offset wholly or in part by this reduction on the defender's side.

This may be illustrated by the table on the next page, assuming a challenger with an acquisition cost of \$5,000 and a defender with the salvage values indicated.

Here the reduction of the challenger's adverse average

[1] The practice of subtracting the defender's salvage value from the challenger's cost is palpably incorrect. See p. 273.

Defender's year of service	Defender's salvage value (beginning of year)	Defender's capital cost for year (loss of salvage during year, plus interest)	When challenge is made at beginning of year indicated			Reduction in challenger's adverse average through subtraction of defender salvage		Reduction in defender's adverse magnitude through omission of next-year capital cost (Col. 2)
			Net investment in challenger ($5,000 − Col. 1)	Challenger's adverse average				
				With 2-year pay-off	With 3-year pay-off	With 2-year pay-off ($2,500 − Col. 4)	With 3-year pay-off ($1,667 − Col. 5)	
	1	2	3	4	5	6	7	8
x	$1,000	$320[a]	$4,000	$2,000	$1,333	$500	$334	$320
$x+1$	800	300	4,200	2,100	1,400	400	267	300
$x+2$	600	280	4,400	2,200	1,467	300	200	280
$x+3$	500	160	4,500	2,250	1,500	250	167	160
$x+4$	400	150	4,600	2,300	1,533	200	134	150
$x+5$	300	140	4,700	2,350	1,567	150	100	140

[a] Salvage value at beginning of year $x - 1$ assumed to be $1,200. Interest is 10 per cent.

through the subtraction of defender salvage from the investment is greater with the 2-year pay-off (Col. 6) and less with the 3-year pay-off (Col. 7) than the reduction in the defender's adverse magnitude through the omission of next-year capital cost (Col. 8). Obviously, this treatment of defender salvage can influence the result either way, depending on the pay-off period and other factors. In general, it is safe to say that the short pay-off method as ordinarily applied protects the defender so long that its salvage value at the time of challenge is seldom of much consequence, but in any event the existence even of substantial value cannot appreciably mitigate the overprotection of the defender we found in the no-salvage case, or the losses from this overprotection.

It is safe to say that few industrial executives would knowingly incur losses of this magnitude from the retarded replacement of equipment. In competition with an enterprise having a correct replacement policy, such penalties could easily be fatal, especially those from a 2-year pay-off. Yet thousands of companies are incurring comparable losses every day in ignorance. We say "comparable losses," because our earlier hypothetical case (page 195) almost certainly indicates their general order of magnitude when the 3-year and 2-year pay-offs are applied to equipment with a correct service life in the vicinity of 10 to 15 years.[1] When the best service life is substantially higher, the penalties for the use of these pay-off periods are of course heavier still.[2]

[1] The results are broadly similar for any reasonable set of assumptions, as the reader can ascertain by comparing examples of his own.

In our imaginary example we have supposed a completely inclusive reckoning of the defender's next-year operating inferiority to the challenger. If this reckoning fails in practice to embrace all elements of defender inferiority (or challenger superiority) as it may if limited to *cost* comparisons alone, it results in a still more extended protection of the incumbent's tenure, and still graver losses from overprotection. To the extent, therefore, that we have "leakage" in the reckoning of next-year inferiority the losses indicated by our hypothetical case tend to be on the low side.

[2] The longer the economic service life of the challenger, the lower, in general, is the ratio of the adverse minimum to the acquisition cost. It follows that the greater is the difference between this minimum and the adverse average obtained with a 2-year or 3-year pay-off calculation.

CORRECT PAY-OFF PERIOD

It is obvious from the drastic reduction in losses as we go in our hypothetical case from a 2-year to a 3-year pay-off that a further extension of the period would eliminate them altogether. There is, of course, *some* period in each case, and for each pay-off formula, that gives the correct result. This is obtained simply by dividing the challenger's correct adverse minimum into its own capital cost. Thus the adverse minimum of the challenger in Table 1 (page 78) being \$1,173 and its capital cost \$5,000, the proper pay-off period is 4.3 years (5,000 ÷ 1,173).

While we can readily reckon the correct pay-off period *if the challenger's adverse minimum is given*, the joker lies in the fact that when we have this minimum there is no need to figure a pay-off at all. The calculation adds nothing to what we already know. On the other hand, if we do *not* have the minimum, we are shooting in the dark in prescribing the period.

III. Conclusion

Our investigation has shown that where the short pay-off requirement is used the selection of the pay-off period itself is the most important factor in the replacement analysis, the difference between a 2-year and a 3-year interval, for example, transcending by far in its effect on the result any likely differences in the various estimates that make up the remainder of the calculation. Since the selection of this period submits to no guiding principle or criterion, it must be, in consequence, purely arbitrary. In the nature of the case, the decision rests largely with management and it is usually binding on the engineer—whether employee or consultant—whose responsibility it is to make the actual analysis. To the extent that this occurs, the engineer's function becomes that of a mere estimator and fact gatherer in a framework that can yield rational results only by accident.

The popularity of the short pay-off requirement is unfortunate both for industry and for the country. For as currently

employed, predominantly for periods of 3 years or less, it is a drag on progress, without justification or excuse save the advantage of convenience. How many mechanical cadavers are being shielded from replacement through the protection of this baneful device no one knows, but their number must be legion. Of this we shall have more to say later, however. In the meantime we turn to another short cut, less popular but nevertheless widely used, the requirement that the challenger yield a prescribed rate of return on the investment.

Chapter XIII

THE RATE-OF-RETURN REQUIREMENT

Having sufficiently explored the most common replacement device, the short pay-off requirement, it behooves us now to consider a less popular, though no less interesting, short cut, the rate-of-return requirement. These two expedients pretty well dominate the field so far as rule-of-thumb solutions are concerned, all others being, by comparison, cats and dogs.

WHAT IS IT?

Like the more popular short pay-off, the rate-of-return requirement is applied in practice in a variety of forms and it is necessary again to select one version for analysis, relegating others to the Appendix.[1] This version is probably the most widely used, and certainly is the simplest. It reckons the challenger's adverse minimum as the sum of straight-line depreciation on the initial net investment (investment net of the defender's salvage value, if any) plus a return at the prescribed rate on this investment. The defender's adverse minimum is the same as by the short pay-off method, namely, its next-year operating inferiority to the challenger. Its capital cost, if any, is disregarded.[2]

Since both the depreciation rate and specified rate of return are computed by this version on the same magnitude, the initial net investment, all we have to do to get the challenger's adverse minimum is to add the two rates together

[1] See p. 276.

[2] The defender's capital cost is presumably taken care of through the subtraction of its salvage value from the acquisition cost of the challenger in reckoning the net investment in the latter, but as we observed earlier this is a poor substitute for the correct treatment. See p. 197.

and apply to this investment. Suppose the cost of the challenger is \$10,000 and the defender salvage value is \$2,000. With depreciation of 10 per cent and a required return of 20 per cent, we take 30 per cent of \$8,000, or \$2,400. Thus the calculation is simplicity itself.

RELATION TO SHORT PAY-OFF REQUIREMENT

It will be evident on a moment's reflection that the difference between this device and the depreciation-plus-interest version of the short pay-off, discussed in the preceding chapter, must lie either in a different capital recovery period or in a different rate of return (interest), or both. For, given the same recovery period and the same rate of return, the two devices are identical.

While the rate-of-return requirement is sometimes applied over the arbitrarily limited capital recovery periods used for the short pay-off calculation, and with similar rates of return or interest, this appears exceptional. As a rule, the capital recovery period is much longer, and the prescribed rate of return much higher. Thus, instead of the 2- and 3-year recoveries prevailingly required for the short pay-off, we are likely to find the period of depreciation 10 years or longer, while in lieu of the conventional interest rates commonly used in the pay-off reckoning (depreciation-plus-interest version) the prescribed rate of return may run 15 or 20 per cent, or even higher.

Obviously, there is no need to discuss the short pay-off again under a different guise, hence we shall have nothing further to say about applications of the rate-of-return requirement that make it substantially, if not entirely, equivalent to its more popular rival. It is sufficient to explore other, and more typical, applications in which it constitutes a separate and independent device.

NOMINAL AND TRUE RATE OF RETURN

Both these devices, it will be noted, compute return or interest on the initial, not the average, investment in the

challenger. In the case of the short pay-off, this is of slight importance, since the interest charge, at the moderate rate usually employed (when used at all) is small relative to the very high depreciation charge, which runs 50 per cent of original investment for the 2-year period and 33 per cent for 3 years. For the rate-of-return requirement, however, it makes a very great difference whether the return is reckoned on the original or the average investment. Since depreciation is charged in this case at a more or less normal rate and since the required rate of return (on original investment) is far above ordinary interest, the return is usually the dominant element in the combination.

It is obvious that when cost of the challenger is recovered through straight-line depreciation charges the average investment outstanding is around half the original; hence an annual return, above depreciation, equal to x per cent on the initial investment is really about $2x$ per cent on the average.[1] The high nominal rates of 15 or 20 per cent annually on the full investment, usually imposed by the rate-of-return requirement, are therefore equivalent to 30 or 40 per cent by the proper reckoning. A very handsome return indeed!

APPLICATION TO HYPOTHETICAL CASE

With this introduction, suppose we explore the operation of the rate-of-return method by a hypothetical case. Let us first assume that the challenger costs $5,000 and that the capital recovery period prescribed for it is 10 years, yielding therefore a 10 per cent depreciation rate. Let us assume further that the defender has an inferiority gradient of $100 a year and salvage values as indicated. We can then compute the rate of return on the challenger when installed at any point in the life of the defender.

[1] With straight-line depreciation, charged currently, average investment is exactly one-half of the initial investment. When such depreciation is charged annually at the close of each year, average investment is slightly larger, in the ratio of $\frac{n+1}{n}$ to n (where n is the number of years in the capital recovery period). Actually, the depreciation is typically more rapid than the straight-line write-off allows for. If the reader is interested in this point, he may refer to p. 278.

TABLE 11

RATES OF RETURN ON A CHALLENGER COSTING $5,000 WHEN INSTALLED AT VARIOUS POINTS IN THE LIFE OF A DEFENDER WITH AN INFERIORITY GRADIENT OF $100 A YEAR AND SALVAGE VALUES AS INDICATED, THE CAPITAL RECOVERY PERIOD FOR THE CHALLENGER BEING 10 YEARS

Year of service of defender	Defender's operating inferiority for service year indicated 1	Defender's salvage value (end of service year) 2	Net investment if challenge occurs at end of defender service year indicated ($5,000 − Col. 2) 3	Rate of return on net investment when challenge occurs at end of defender service year indicated,[a] per cent 4	Rate of return on gross investment (ignoring defender salvage value),[a] per cent 5
1	$ 0	$4,200	$ 800	2.5	− 8.0
2	100	3,500	1,500	3.3	− 6.0
3	200	2,900	2,100	4.3	− 4.0
4	300	2,400	2,600	5.4	− 2.0
5	400	2,000	3,000	6.7	0
6	500	1,700	3,300	8.2	2.0
7	600	1,400	3,600	9.4	4.0
8	700	1,200	3,800	11.1	6.0
9	800	1,000	4,000	12.5	8.0
10	900	800	4,200	13.8	10.0
11	1,000	600	4,400	15.0	12.0
12	1,100	500	4,500	16.7	14.0
13	1,200	400	4,600	18.2	16.0
14	1,300	300	4,700	19.8	18.0
15	1,400	200	4,800	21.3	20.0
20	1,900	0	5,000	30.0	30.0
30	2,900	0	5,000	50.0	50.0

[a] The formula for deriving these figures is as follows:

$$\text{Rate of return} = \frac{\text{defender's next-year operating inferiority} - \text{challenger depreciation}}{\text{net investment in challenger}}$$

When defender salvage value is disregarded (Col. 5), the challenger investment is uniformly $5,000 regardless of the age of the defender, and depreciation is always $500 a year. All that is required, therefore, is to subtract $500 from the defender's next-year inferiority (Col. 1) and divide the remainder by $5,000. When salvage value is regarded (Col. 4), the procedure is slightly more complicated. Here a different net investment must first be computed for each age of the defender, with a corresponding annual depreciation. This depreciation is then subtracted from the appropriate next-year defender inferiority (Col. 1) and the remainder is divided by the net investment. For example, when the defender is 10 years old, net investment is $4,200. Depreciation is therefore $420. The next-year (eleventh-year) inferiority being $1,000, the excess over depreciation is $580, which is 13.8 per cent of $4,200, as shown.

THE ROAD TO RICHES

Here is an interesting picture, surely. The annual rate of return on the replacement investment increases steadily as the defender ages, with the sky the limit. All that is necessary to get a higher return is to wait a little longer. Thus if the owner of the incumbent machine demands 10 per cent on the replacement investment, he will keep it for 8 years (Col. 4); if he wants 20 per cent, he will keep it 15 years; if he insists on 30 per cent, he will add another 5 years; if he has really big ideas and shoots for 50 per cent, he will add 10 years on top of that. But why stop here? A return of 100 per cent per year is his for the asking—or rather, for the waiting. Time is on his side. All he needs to do is to keep his beloved machine to the hoary age of 55 years.[1]

If the rate-of-return approach to replacement is correct, we can only marvel that its proponents are satisfied with such piddling rates of return as 15 or 20 per cent, (actually, as we have seen, 30 or 40 per cent). How can they fail so abysmally, at their own cost, to realize the profits of procrastination? One would suppose that if they believed the logic of their method, they would think in terms of hundreds, even thousands, per cent. Instead they stop, for no clear reason, on the bottom rungs of a ladder stretching to the heavens, the ascent fully in their power. Why this strange act of renunciation? Are we dealing here with an outbreak of commercial asceticism? Hardly. We are dealing with a case of cold feet. The practitioners of the rate-of-return method, lacking any valid criterion of how high on the ladder to climb, choose to huddle near the familiar earth, grouped for the most part on the rungs marked 15 and 20 per cent. Thus far their desire for gain sustains them; beyond that level they grow faint. The result, while psychologically explainable, is logically indefensible. If 20 per cent is good, 50 per cent is better, and 100 per cent is better still.

[1] Assuming a continuation of the inferiority gradient of $100 a year throughout.

THE JOKER

Obviously, there must be some joker in this method, and indeed there is. It treats as net return on the replacement investment what is in part simply relief from losses occasioned by the undue deferment of replacement. We may illustrate the point by analogy. A corporation has a president 70 years of age who in the judgment of the directors can be retired and replaced at a net annual advantage to the company of $10,000. Someone points out, however, that if he is kept to age 75, and if he suffers in the interval the increasing decrepitude normally to be expected, the gain from replacing him at that time will be $50,000 a year, while it should be substantially higher still, say $100,000 at the age of 80. It is urged, therefore, that his retirement should be deferred. The genius advancing this proposal is recognized at once as a candidate for the booby hatch, yet it is no different in principle from the rate-of-return requirement.

No one can deny that the advantage of $100,000 a year (if such it is) from retiring the president at 80 is a real advantage, *given the situation then prevailing*. The question is whether this situation should be deliberately created for the sake of reaping this gain. Similarly, the question is whether a machine should be retained beyond its proper service life in order to get a larger benefit from its replacement. The answer in both cases is obvious. The executive who knowingly and wilfully follows this practice should sleep on a spike bed to enjoy the relief of getting up in the morning.

It is obvious that if industry could make a genuine net profit of 20, 50, or 100 per cent per annum on the investment in replacement assets, no company could afford to acquire new facilities for other than replacement purposes. There is rarely that kind of profit available for completely new enterprises. The best way to go into business would be to buy old equipment first, then immediately replace it with new. The more decrepit this old equipment, the more ill-adapted for the operation in hand, the better for the purchaser; he could get a proportionately higher return from its replacement. This

return would be limited, indeed, only by the skill and resourcefulness with which he exploited the junk market.

We know of no company that has fallen for this get-rich-quick scheme, yet many concerns that would never dream of *buying* old equipment in order to realize a 15 or 20 (really 30 or 40) per cent return on the investment in its replacement, nevertheless continue for this reason to hold on to old equipment they already have. There is no reason to suppose that a new machine earns more because it replaces a previous machine on a particular job than it would earn if otherwise set up on the same job. There is no evidence that old establishments operating entirely with replacement equipment earn more than new ones operating with original equipment, even when they have consistently bought all their replacements to return 15 to 20 per cent on the initial investment. Many such enterprises fail year after year to show a profit of more than a small fraction of the 30 to 40 per cent they should theoretically make (on their equipment account) if the earnings of their replacements were really as large as estimated at the time of acquisition.[1]

The reason these estimates seldom materialize in the profit-and-loss statement is not far to seek. In order that replacements may yield an apparent annual return of 15 to 20 per cent on the original (or 30 to 40 per cent on the average) investment, it is necessary to keep the existing equipment beyond the proper point of retirement. This overretention may develop losses (as compared with a correct replacement policy) and may keep the profits of the enterprise down. The apparent return on replacement investment may thus represent in part simply relief from these losses.

It must be obvious that industry cannot get rich on gains arising from the correction of situations that should not

[1] If a company consistently bought replacements to yield 15 to 20 per cent annually on the original investment and if this return actually appeared as profit, the rate on the net equipment account should exceed 15 to 20 per cent by the ratio of the gross account to the net. If this ratio were approximately 2 to 1, as it would be for a fully seasoned group of assets, the profit rate on the net account would be double, or 30 to 40 per cent.

have been allowed to occur. Such gains management should eschew as it would the plague, by avoiding the situations that make them possible. This it can do by *keeping* costs at a minimum (and revenue at a maximum) all the time.

FALSE PROFITS

Suppose we look further at these high returns from replacement. They are often referred to by advocates of the rate-of-return requirement as "profit." What is wrong with this conception?

Real profit is an excess of revenue over cost. As such, it can be measured, obviously, only for an operation in which both revenue and cost are determinable. When we have such an operation, however, it almost always involves the collaboration of numerous elements, human and mechanical, all contributing to the common result. Profit is a *joint product* of this collaboration. For this reason it is ordinarily impossible to measure the separate contribution to profit of any one element in the operation, such as a single machine.

What we *can* attempt to measure, and what it should be our object to measure in replacement analyses, are the *differences* in the profit of the entire operation resulting from the use of various alternatives to the machine. Thus, if alternative *A*, by reason of superior service, can add \$1,000 next year to the revenue of the operation, while subtracting \$1,000 from its cost, it will make a difference of +\$2,000 in profit. If alternative *B* renders a service of the same quality as the incumbent, leaving revenue unchanged, but adds \$1,000 in cost, it will make a difference of −\$1,000. Thus we can determine *changes* in the total profit occasioned by such alternatives without ever knowing, or needing to know, the absolute contribution of any one of them.

But are these differences in profit themselves profit? Consider alternative *A*, just mentioned. As compared with the incumbent machine, *A* enhances the next-year profit of the operation by \$2,000. As compared with *A*, however, the incumbent *reduces* this profit by the same amount. We are

dealing here with relativity. The same $2,000 difference is at once the relative gain, or profit, from using *A* next year, and the relative loss from using the present machine. Thus the answer depends on the point of view, or rather, on the point of measurement.

Now if both points of measurement were equally valid, we should have to acknowledge the impossibility of deciding whether the difference between alternatives is really gain or loss. But they are not of equal validity. The object of business management is to minimize cost and maximize revenue, in other words, to maximize profit. The machine that accomplishes this object has therefore a unique status; it is the touchstone by which all others must be judged, in accordance with the principle of "top-down measurement," propounded earlier (page 33). Once we accept this machine as the standard, there can be no profit from the use of others, but only *loss*. It follows that if the rate-of-return method yields large apparent profits from delayed replacement, it is because it measures in the wrong direction, from below upward.

This is not the only defect in the device, however. It not only measures in the wrong direction; the measurement is otherwise incorrect, principally for three reasons: (1) It prescribes a rate of return unrelated to the time cost of money, (2) it ignores the challenger's inferiority gradient, and (3) it sets the challenger's service life arbitrarily. Let us consider these points in order.

COST OF MONEY. As we saw in Chap. X, a proper allowance for interest is a necessary and legitimate charge against investment in the challenger. But as we saw also, this allowance should bear a close relation to the actual cost of money to the enterprise concerned. It is obvious without discussion that rates of 30 to 40 per cent per annum (on the average investment) commonly imposed by the rate-of-return method are unrelated to any reasonable charge. *They constitute an improper handicap to replacement.*

Consider, for example, a challenger costing $10,000. If the correct service life is 10 years and the time cost of money

10 per cent, the correct annual capital charge is $1,628.[1] As calculated by the rate-of-return method, however, a 20 per cent requirement (on the initial investment) yields $3,000.[2] If the calculation were otherwise correct, this excess charge of $1,372 a year against the challenger would retard replacement, perhaps for many years. But the calculation (under the rate-of-return method) is not otherwise correct. It happens, moreover, that the most important remaining error, disregard of the challenger's inferiority gradient, yields a bias in the opposite direction. Let us consider this briefly.

CHALLENGER'S INFERIORITY GRADIENT. As we have repeatedly emphasized, the challenger's adverse minimum, properly computed, is a combination of capital cost and operating inferiority. Since the latter appears in any asset subject to deterioration or obsolescence, or both, it is normally an important component. Take, for example, the adverse minimum of the challenger described in Table 1 (page 78). Of $1,173, $439 is operating inferiority. Or consider that of the Table 2 challenger (page 81). Here inferiority makes up $337 out of $1,132. Obviously, the omission of this element would result in a premature replacement signal.

The rate-of-return method is guilty of precisely this omission. It takes cognizance of the challenger's capital cost only. However, the understatement of the adverse minimum from this cause is countered by an overstatement of capital cost itself by reason of the fantastic rates of interest charged. If it yields the correct replacement signal, therefore, or anywhere near it, it must be because the two errors (and others) accidentally compensate. Obviously, any procedure that depends on a fortuitous compensation of errors is inherently absurd.

CHALLENGER'S SERVICE LIFE. It is a curious feature of this method that it affords no procedure or rationale for determin-

[1] Assuming no terminal salvage value. This is the uniform annual equivalent of $10,000 for 10 years at 10 per cent interest.

[2] Assuming no deduction from the cost of the challenger for defender salvage value. The $3,000 consists of $2,000 return and $1,000 depreciation.

ing the challenger's service life. This should be the period that yields the lowest annual life average of capital cost and operating inferiority combined, but since the method takes no cognizance of inferiority, charging the challenger with capital cost alone, no determination of the optimum service life is possible. For obviously the annual capital cost is at a minimum when the capital recovery period is infinity. There are thus no theoretical bounds or limits to the extension of the assumed life.

For example, if the challenger costs $10,000 and if the required return (on the initial investment) is 20 per cent, the annual capital cost is $3,000 when the assumed life is 10 years, $2,667 when it is 15 years, $2,500 when it is 20 years, $2,200 when it is 50 years, and $2,000 when it is infinity. If the life is arbitrarily fixed at 10 years or some other "reasonable" figure, as it normally is, this is simply a common-sense decision, extraneous, indeed alien, to the method itself. Strict logic requires that the assumed life be infinity in all cases.

Thus for the rate-of-return method to arrive at the right answer it is necessary not only for the bias from an excessive time cost of money to offset by accident the bias from the omission of the challenger's inferiority gradient; it is necessary also for the challenger service life, conjured arbitrarily from thin air, to coincide by accident with the correct life.[1] The probability of such a concurrence the reader can judge for himself.

LOSSES FROM USE OF THE DEVICE

In the preceding chapter, we analysed at some length the losses (as compared with a correct replacement policy) resulting from the use of the short pay-off device. A similar computation is easy for losses occasioned by the rate-of-return device.

Suppose we take again the challenger of Table 1 (page

[1] This is by no means a complete statement. There are other errors in the method—for example, the treatment of defender salvage value (p. 197). But we need not belabor further a procedure sufficiently condemned by more important faults.

78). Its correct adverse minimum is $1,173. Since it costs $5,000, the minima derived by the rate-of-return method are as follows for selected rates (assuming depreciation of 10 per cent).

Required rate of return on initial investment, per cent	Resulting adverse minimum	Excess over correct figure
10	$1,000	$ −73
15	1,250	77
20	1,500	327
25	1,750	577
30	2,000	827
40	2,500	1,327

In this case, the adverse minima derived from the 10 and 15 per cent rates are not far off. For rates above 15 per cent, however, the error mounts rapidly, reaching $1,327 at 40 per cent.

To compute the loss from using the method in this instance it is necessary to assume the inferiority gradient of the defender during the period of overprotection. Let us say this is $100 a year. On this basis the losses are as follows:

Required rate of return, per cent	Period of overprotection of defender,[a] years	Loss from overprotection[b]	Present worth of loss at beginning of period[c]
20	4	$ 600	$ 438
25	6	1,500	968
30	9	3,600	1,942
40	14	9,100	3,680

[a] Assuming defender has excess inferiority of zero for the first year.
[b] Cumulative excess of defender inferiority over $1,173, the challenger's correct adverse minimum.
[c] Excess inferiority discounted to beginning of period of overprotection at 10 per cent, assumed to be the correct cost of money.

THE "CORRECT" RATE OF RETURN

In discussing the short pay-off requirement, we pointed out that there must be *some* pay-off period for each form and

application of the device that gives the correct replacement signal. This observation can be generalized. There is necessarily at least one value of the variable (or combination of variables) in any replacement device, however irrational or even absurd, that will yield the correct signal for any given application. To put it otherwise, not even a wrong method can be wrong invariably and without exception. Applied to the method in hand, this means that there is in every instance one rate of return that gives the right answer. Thus in the case of the Table 1 challenger employed in the preceding illustration, this rate is 13.5 per cent.[1]

While this rate is "correct" in the sense that it gives the proper replacement signal, the rate-of-return method affords no means of determining it. Thus we find ourselves in the same quandary or predicament confronted earlier in the case of the "correct" pay-off period: To find the "correct" period (or in this case, the rate of return) we must already have learned the challenger's adverse minimum from other sources. But if we already know this, we have no need or use for more. Surely it is a curious method of replacement analysis that requires us to know the answer in order to arrive at it.

Like the more popular device, the short pay-off, the rate-of-return requirement is a theoretical and practical monstrosity. It can be right only by chance. As ordinarily applied, it is probably somewhat less conducive than the short pay-off to delayed replacement and for that reason may be less objectionable—if we may damn with faint praise. But it is at best a dubious reliance, and the sooner it is abandoned, the better.

[1] This is the rate of return on the \$5,000 the challenger costs, which, added to depreciation at 10 per cent, will give the correct adverse minimum of \$1,173.

Chapter XIV

PRESENT PRACTICE CONSIDERED FURTHER

We described in an earlier chapter the failure of the minimum-average-cost formula to allow for future obsolescence, and the apparent disposition of some of its advocates to compensate for this deficiency by the use of an arbitrarily shortened capital recovery period for the challenger in cases where the risk of such obsolescence is deemed substantial. We commented on the unreliability and general unsatisfactoriness of this adjustment, suggesting that it constitutes in fact an abandonment of the formula for something that is neither fish, flesh, nor fowl. If this is the pass to which a respectable replacement theory like minimum average cost has come, what shall we say of the motley brood of empirical devices that have no theoretical parentage whatever? Of some of them it must be said, certainly, that they border on superstition.

By all odds the most important of these devices we have considered at length, the short pay-off requirement and the rate-of-return requirement. While their origins are obscure, as we explained earlier, they are obviously specimens of industrial folklore rather than the product of sophisticated theorizing. They are a legacy from the prescientific era. If recently one of these devices, the short pay-off, has attained a measure of pseudorespectability as an alternative to minimum average cost in cases involving future obsolescence, this in no way alters its origin or its essential character. It remains, with its companion the rate-of-return requirement, a theoretical monstrosity.

That American industry, devoted to the ideal of "scien-

tific" management, should have nothing better than these ancient conventions to test the replaceability of its equipment is astonishing to say the least. There is something quite out of character in the continued acceptance and use of such primitive expedients, especially in an area as important as equipment policy. Indeed, when we consider the advanced techniques now employed in other areas of business management, we may well wonder if equipment policy is not, in general, the most backward sector of all. We are inclined to think it is.

If the short pay-off and rate-of-return requirements are primitive, unscientific, and blind, certainly we can say no more for methods of replacement analysis that depend on pure hunch, without benefit even of conventional rules of thumb. As we indicated in the opening chapter of this study, a substantial proportion of the replacement decisions in American industry are made on this basis. They rest simply on judgment and intuition. Whether bad tests of replaceability are better than none is a fair question, but the fact that this is the practical alternative, as replacement analysis is now conducted, emphasizes the urgent need for better analytical procedures.

CAN THE PRESENT DEVICES BE SALVAGED?

The question arises naturally enough whether the short pay-off and rate-of-return requirements may not somehow be modified or adapted so that American industry can continue to use them, but to better effect.

One suggestion for the rationalization of the short pay-off is particularly appealing at first glance. It is proposed that the length of the pay-off period be geared to the prospective service life of the challenger, either as a fixed percentage thereof or on some sliding-scale arrangement. This done, the estimate of the service life would automatically indicate the appropriate pay-off period. The challenger's adverse minimum would then be available at once simply by dividing this period (in years) into the required investment.

When the challenger has no prospect of effective salvage value, it is possible to define the relation (as indicated by our own procedure) between the service life and the pay-off period that yields the correct adverse minimum. In this case the relation depends on the interest rate and the service life only.[1] When we must reckon with salvage value, however, the pattern becomes hopelessly complicated. Here there can be no general scheme or formula for deducing the pay-off period from the service life. For the relation between the two is different for each different pattern of salvage values. With one pattern the appropriate period may be a small fraction of the life span; with another it may be several times its length.

While the proposal is thus inapplicable to the class of cases in which challenger salvage values must be taken into account, it is by no means an instantaneous solution for no-salvage cases. For even here the relation between the service life and the pay-off period is complex, as the reader may infer from a glance at the equation that describes it:

$$\text{Pay-off period (in years)} = \frac{in + \dfrac{1}{(1+i)^n} - 1}{i^2 n}$$

when i is the interest rate (in decimals) and n is the number of years in the service life.[2] The nature of the relation is shown graphically in the chart on the page following.

Clearly there is no semblance of uniformity or constancy in the ratio of the pay-off period to the service life.[3] Thus it ranges from 54 per cent for a 5-year challenger at 5 per cent interest to 16 per cent for a 25-year challenger at 20 per cent.

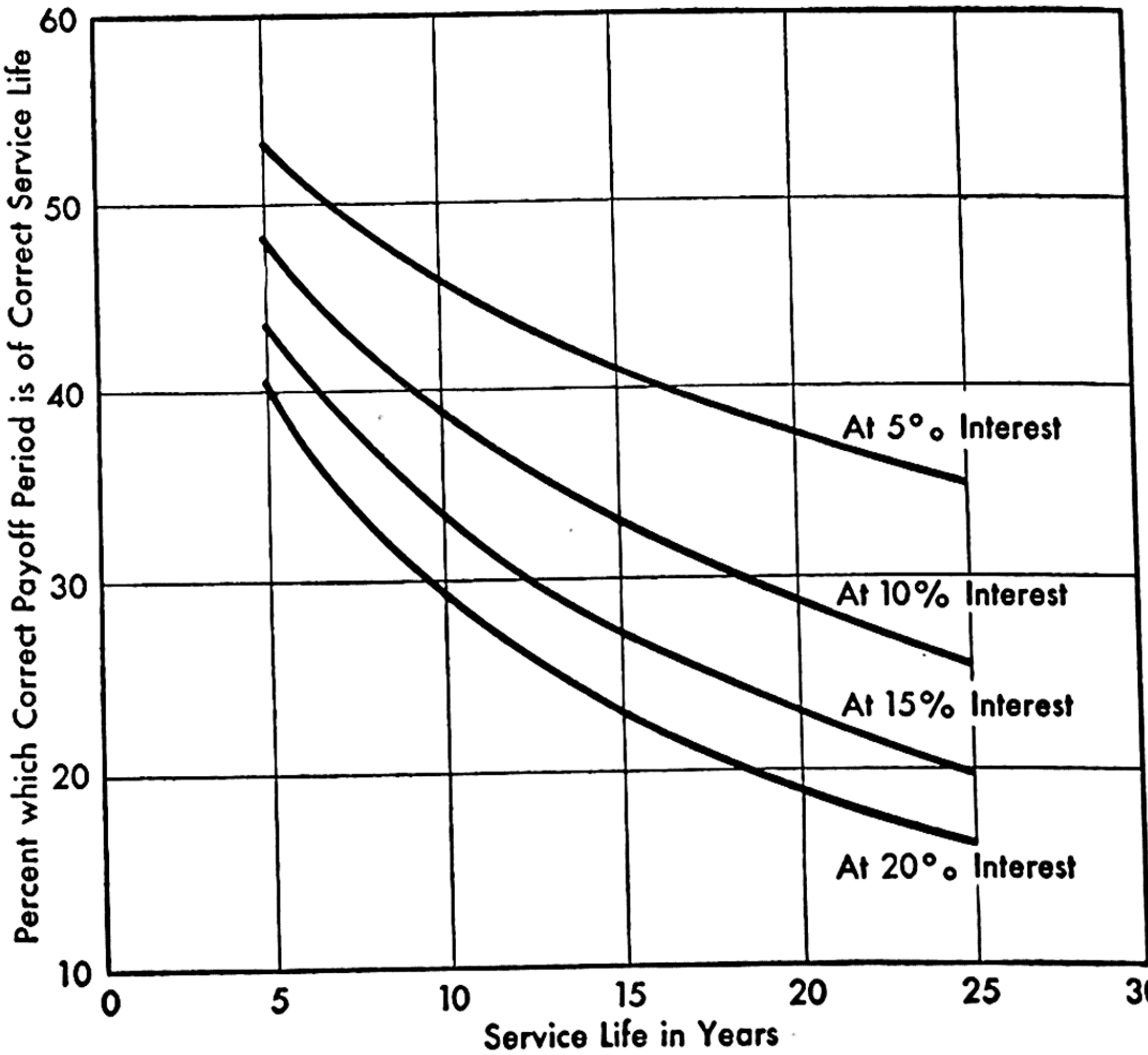
[1] As we have seen previously, the service life is determined in turn by the interest rate and the gradient/cost ratio.

[2] For derivation, see p. 282.

[3] It may be pertinent to remind the reader again that since we are concerned in this study only with *primary* replacements all references to "service life" relate to primary service, that is to say, to service prior to the first replacement. This may or may not coincide with the total life span of the asset, depending on whether it is retired at the first replacement or transferred to some other assignment.

CHART 7

PERCENTAGE OF THE SERVICE LIFE THAT SHOULD BE TAKEN AS THE PAY-OFF PERIOD TO YIELD THE SAME ADVERSE MINIMUM AS OUR OWN PROCEDURE, FOR A CHALLENGER HAVING NO EFFECTIVE SALVAGE VALUE, AND FOR VARIOUS RATES OF INTEREST[a]



[a] The calculations assume the simple (no-interest) version of the short pay-off. They assume also that defender salvage value, if any, is *not* deducted from the cost of the challenger. The latter assumption is contrary to prevailing usage, as we have seen. When the defender's salvage value is so deducted (and when its next-year capital cost is omitted at the same time from its adverse minimum), the relation between the challenger's service life and the proper pay-off period becomes hopelessly complicated. Under these circumstances the period is no longer the one that will yield the correct adverse minimum for the challenger; it is the one that will yield an adverse minimum that is low by the same amount that the defender's minimum is low by reason of the exclusion of its next-year capital cost. For further discussion of this point, see p. 197.

Even with the interest rate held constant the ratio varies widely. With a 10 per cent rate, for example, the pay-off period ranges from 48 per cent of a 5-year service life to 25 per cent of a 25-year service life.

While it is possible in the no-salvage case to derive the pay-off period from the service life by formula and while it is also possible, as the chart demonstrates, to work up a table or diagram from which the period can be read off, either directly or by interpolation, the question properly arises whether the game is worth the candle.[1] We doubt very much if it is. Neither route to the challenger's adverse minimum (the only object in deriving the appropriate pay-off period is of course to compute this minimum) seems to us so simple and direct as the short-cut formulas for the no-salvage case supplied earlier pages 95 and 107.

Since there is a better solution than the short pay-off in the no-salvage case and since the device is totally useless or worse when salvage value has to be taken into account, we see no reason to attempt its perpetuation at all. The same conclusion applies to the less popular rate-of-return device. No one, so far as we are aware, has yet tried to rationalize the required rate of return by tying it to the estimated service life, and in default of other alternatives the device remains completely blind.

The matter is even worse than we have made it. For if it is impracticable to salvage even the simplest versions of the short pay-off and rate-of-return requirements, what must we say of the innumerable and erratic variations of each that appear in practice?[2] If we compound the problem by this diversity, we pass quickly from the impracticable to the impossible.

Not to extend the discussion, we shall simply reiterate that we regard the two devices under discussion as irredeem-

[1] While Chart 7 shows the *ratio* of the pay-off period to the service life, by interest rate and length of life, it is of course possible to develop a diagram from which the pay-off period (in years) can be read directly, once the interest rate and service life are supplied. Such a diagram is presented in Chart 8, p. 222.

[2] A sampling of these variants may be found on pp. 269 and 276.

able. It is true, as we indicated earlier, that they are not invariably wrong and that there is necessarily in every case some pay-off period or some rate of return that gives the right replacement signal. But as we also indicated, we can identify this period or rate only when we have first determined the challenger's adverse minimum by a correct method of analysis. Again, this amounts to saying that we must first know the answer in order to arrive at it.

BIAS IN THE APPLICATION OF THE DEVICES

We have previously declared our belief that as actually applied in American industry the short pay-off and rate-of-return devices lead prevailingly to a retardation of replacement. We know of no way to prove this proposition conclusively, however, except to test by a better method of analysis a representative sample of replacement decisions arrived at by the use of these devices. We have not carried out such an investigation, nor, so far as we know, has anyone else. Until this is done, no final judgment is possible.

When we consider the extraordinary diversity, not only in the form of these devices, but also in the pay-off periods or rates of return at which they are applied, it appears probable in any case that the error from their use is not always in one direction. There must be instances of premature replacement resulting from too long pay-off periods or from too low required rates of return. After all, when no one knows what the period or the rate *should* be there are bound to be bad guesses on both sides. Our belief that the predominant bias is toward delayed replacement rests on an analysis of what appears to be the prevailing practice in the application of these devices.

Unfortunately, we know of no tabulation showing the frequency of various required rates of return, and we must be content, therefore, with the impression already reported from a casual sampling of cases that the most common range appears to be 15 to 20 per cent (on the initial investment). When we add to this an assumed depreciation of 10 per cent, also common apparently, we obtain a challenger's adverse minimum

of 25 to 30 per cent of the investment (taken usually net of defender salvage value). This is equivalent to a pay-off period of 3.3 to 4 years as ordinarily reckoned.

If our impression of the prevailing practice under the rate-of-return method is correct, it appears, as we indicated earlier, considerably less conducive to delayed replacement than the short pay-off requirement. For as to the latter we do have a few tabulations (above, page 189) which suggest that periods of 3 years or less are employed in the majority of cases. Here the presumption in favor of retarded replacement becomes very strong.

The presumption is confirmed by the chart on the next page, which shows the appropriate pay-off periods for various challenger service lives (as determined by our own procedure) for the no-salvage case, the only one, as we have seen, for which the calculation is possible.

For the no-salvage case, the 2-year and 3-year pay-offs are good only for very short service lives or for very high interest rates, or both. For a moderate interest rate such as 10 per cent, the popular 2-year period is appropriate only for service lives of less than 5 years, the 3-year period for lives under 7 years. For lives of 15 to 20 years, which are common, the appropriate pay-off ranges between 5 and 6 years.

It must be remembered that this is the picture for a challenger without effective salvage value. Accordingly, it reflects the *minimum* pay-off period for any given service life and interest rate. For when effective salvage value is present, the correct period is bound to be longer than the chart prescribes.[1] Indeed for very short service lives it may be, relatively, much longer. This qualification must be kept in mind in comparing prevailing practice in the application of the short pay-off with the standards indicated. For certainly a

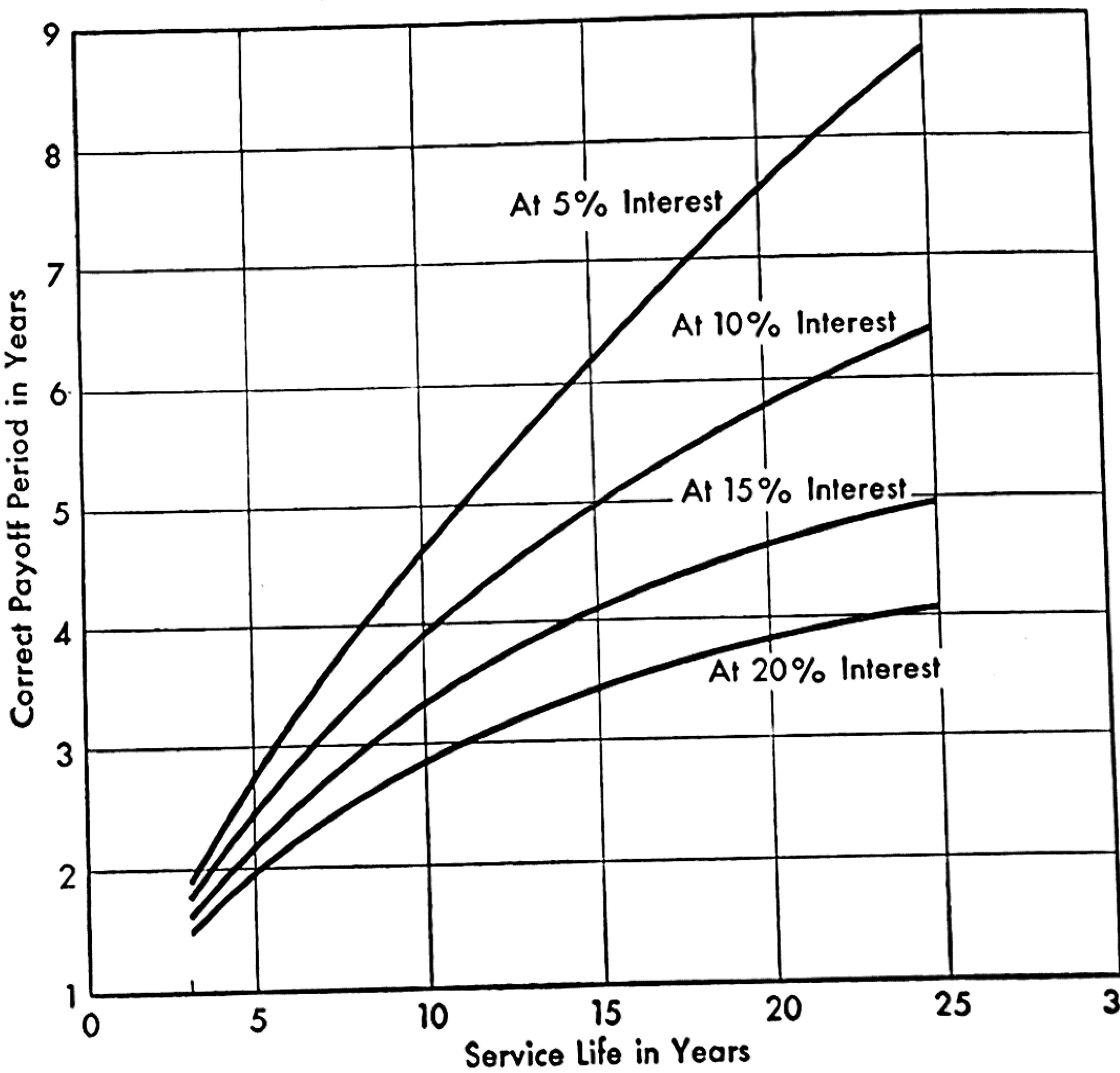
[1] As we pointed out earlier (p. 82), effective salvage value *lowers* the adverse minimum and *shortens* the service life as compared with a no-salvage challenger having the same cost and inferiority gradient. This means that the pay-off period yielding the same adverse minimum as our own method is *longer* by reason of salvage value, while associated with a reduced service life.

considerable proportion of all challengers to which the device is applied do have effective salvage value.

Anyone familiar with American practice will acknowledge, we believe, that the very short pay-offs of 2 and 3 years are widely used for challengers with prospective service lives far longer than those for which the chart indicates such pay-offs to be appropriate. When we add that in many of these applications there is effective challenger salvage value, the excessive brevity of the periods prescribed becomes even more

CHART 8

PAY-OFF PERIODS WHICH YIELD THE SAME ADVERSE MINIMUM AS OUR OWN PROCEDURE, FOR A CHALLENGER HAVING NO EFFECTIVE SALVAGE VALUE, AND FOR VARIOUS RATES OF INTEREST[a]



[a] Here, as in Chart 7, we assume the simple, or no-interest, version of the short pay-off. We assume also that defender salvage value, if any, is *not* deducted from the challenger's cost. The second assumption is discussed briefly in the footnote to Chart 7.

striking. There is at least a prima-facie case, therefore, for a widespread retardation of replacement through the use of this device. The presumption is less strong, as we have indicated, for the rate-of-return requirement, though even here it carries considerable weight.[1]

AMERICAN PRACTICE IN GENERAL

The foregoing observations on the application of the short pay-off and rate-of-return devices in American industry should not be pressed too far, and we have no desire to do so. While we can get some clue to the character of existing practice from the consideration of these popular tests of replaceability, it is at best a clue only.[2] As we said before, the one way to obtain a conclusive appraisal is to test a representative sample of cases by an acceptable method of replacement analysis. Lacking such an appraisal, we must rely, necessarily, on impressions.

On an impressionistic basis, therefore, we venture to say that while the defects of American equipment policy are due in part to the tests of replaceability commonly employed, they are due quite as much to ignorance, poor organization of equipment policy, and lack of capital. Suppose we consider these factors in order.

[1] The presumption is strengthened in both cases by the fact, previously noted (p. 183), that the defender's adverse minimum is frequently understated through the omission of noncost elements from the reckoning of its next-year operating inferiority (challenger superiority). Indeed the calculation of cost inferiority is itself incomplete in many cases, being limited to certain elements only, such as, for example, direct labor. Understatement of the defender's adverse minimum leads, of course, to an aggravation of the results from the overstatement of the challenger's minimum by reason of excessively short pay-off requirements.

[2] The somewhat tenuous character of this clue arises not only from the necessary limitation of Chart 8 to no-salvage cases, but from the equally necessary exclusion of the common practice of subtracting defender salvage value from the challenger's cost. We can tell the *direction*, though not the amount, of the error in the plotted relationships as applied to challengers with effective salvage value, but we can tell neither the direction nor the amount by which these relationships depart from those that would apply if the investment in the challenger were reckoned, as it ordinarily is, net of defender salvage value. As we indicated earlier (p. 199), this reckoning can move the replacement signal either way, depending on the circumstances of the case and the pay-off period used. Presumably, defender salvage value is relatively small in most cases, and when this is true the second difficulty is not too important.

IGNORANCE

If we are correct in our appraisal of existing replacement formulas and devices, we can reiterate that save for the relatively few cases for which the minimum-average-cost formula is appropriate (cases involving no challenger obsolescence), American industry has had nothing better to work with than folklore and superstition. This may go far to account for the fact, already cited, that a sizable proportion of replacement decisions are made without benefit of any rule or formula whatsoever. In any event, the lack of a usable test of replaceability has made it difficult for even an alert and progressive management to determine a proper equipment policy and has made it easy for less able management to coast along with a bad policy in costly, if blissful, ignorance of its consequences.

POOR ORGANIZATION OF EQUIPMENT POLICY

While the want of a reasonable method of replacement analysis is itself a prime cause of inertia in this phase of management, it must be said in all honesty that this is at most but a partial extenuation of the lack of intelligence and organization so often found in the administration of equipment policy. We have no comprehensive statistics on the point, but we can say from diligent inquiry and observation that in a very substantial proportion of manufacturing enterprises there is no official whose special business it is to make a continuing study of the possibilities of remechanization and to bring these possibilities up for decision. Since the regular operating executives are generally too busy trying to get the maximum production from existing equipment to give sufficient time and attention to the evaluation of alternatives, the result is a haphazard, hit-or-miss procedure that fails by a wide margin to exploit the available replacement opportunities, even as judged by the possibly inadequate standard the company is accustomed to apply.[1]

[1] Obviously, the more replaceability depends on developments external to the existing equipment, that is to say, on obsolescence, the more serious the consequences of a defective organization of equipment policy are likely to be.

In this connection, it is pertinent to cite the response to the following questions addressed (with others) to a number of member companies of the Machinery Institute.[1]

Ques.: Do you have an equipment engineer who specializes in making replacement studies?

	Per Cent of Replies
Yes	28
No	72

Ques.: Do you make a regular, periodic review of your equipment situation for the purpose of improvement and modernization?

	Per Cent of Replies
Yes	35
No	65[2]

Ques.: Are reequipment expenditures budgeted ahead?

	Per Cent of Replies
Yes	32
No	68

We do not imply for a moment that a negative response to these questions is necessarily evidence of a poor organization of equipment policy. Poor organization for a large company may not be so for a small one, and a system (or lack of it) that works satisfactorily in one case may be bad in another regardless of size. There are a lot of variables. Nevertheless we cannot avoid the suspicion that the high proportion of negatives does reflect a considerable degree of backwardness both in organization and practice.

If there is widespread inertia in the exploration and analysis of reequipment possibilities, it is to be found also

[1] Returns from a questionnaire on replacement and depreciation policy distributed in the spring of 1948. The three inquiries reported here elicited 196, 192, and 186 tabulable replies, respectively.

[2] Includes a number of replies stating that the situation is reviewed "continuously."

in the reviewing of proposals actually developed. Many companies carry proposals involving more than a modest outlay (frequently $5,000) to the top levels of management, including the board of directors, for final decision. Ultimate authority rests, therefore, with officials lacking any intimate familiarity with the technological details involved and unable to give more than cursory attention to run-of-mine cases. There is a widespread belief among the technical levels of management that it is difficult to get favorable action on such cases unless the estimated advantages are spectacular, especially at times when the financial position of the company is less than flush.

This view is confirmed by the observation of a leading machine-tool builder, who recently commented as follows:

> There are many reasons for the inertia which delays needed rehabilitation, but first in importance is lack of understanding of the value of up-to-the-minute machine tools by the "front office" of industry. . . . Many a sound program submitted by a competent shop supervisor gets no farther than the wastebasket next to the Board of Directors' table, because many of those who hold the purse strings have no real understanding of the profit-making potentials in modern tools. . . . Financial managers frequently are not close enough to the production department to realize that the very existence of their company may depend on utilizing machines which, by cutting costs and increasing production, may successfully meet critical competition.[1]

Again we can get further light on the subject by reference to the Institute questionnaire referred to a moment ago:

Ques.: Who makes the initial recommendation on re-equipment outlays?

	Per Cent of Replies[2]
Superintendents, works managers, and department heads	63
Engineers or master mechanics	15
Foremen	15
"Top management"	7

[1] From the presidential address of A. G. Bryant before the National Machine Tool Builders' Association, Apr. 8, 1948.

[2] Total number of replies, 177.

Ques.: Who makes the final decision on reequipment outlays?

	Per Cent of Replies[1]
Presidents or chief executive officers	61
Board of directors or executive committee	39

The location of final decision, even in routine cases, at the top of the managerial pyramid has another effect not yet mentioned. Equipment salesmen do not, as a rule, have access to officials with power to sign on the dotted line. Their salesmanship can reach these officials only at second hand, transmitted (if at all) in diluted form by the mechanical executives who initiate reequipment proposals. In this transmittal it loses, naturally, large part of its effectiveness. This isolation of the salesman from the center of decision is indicated by the replies to another interrogation in the questionnaire:

Ques.: How high in the customer's management do your salesmen typically have access and contact?

	Per Cent of Replies[2]
General management	30
Other	70

Again we are not intimating that the requirement for clearance at the top level is always or necessarily an impediment to proper reequipment policy. This requirement may mean one thing in one company and something else in another, depending on the size of the enterprise, the personalities involved, and many other factors. Obviously some form and degree of top-level control is indispensable. But it may well be doubted if in general the prevailing setup does not involve, for routine cases at least, an unfortunate divorce of power and authority on the one hand from knowledge and experience on the other.

[1] Total number of replies, 188.
[2] Total number of replies, 128.

LACK OF CAPITAL

If poor organization of equipment policy is responsible in part for backward mechanization in American industry, another contributing factor, and a very important one indeed, is lack of capital. We observed some time ago, in discussing the interest rate for replacement analysis, that many companies go along year after year making only such replacements as their internally available funds permit. If these funds are inadequate, such concerns may live in a state of chronic undermechanization, a reflection fundamentally of the fact that they are undercapitalized.

In a great many cases, especially with small enterprises, this undercapitalization may be more or less inescapable, owing to the prohibitive inducements necessary to draw additional outside money into the business. If it is really so, there is obviously not much that can be done to improve replacement policy except to use most advantageously the limited funds available. It is perfectly obvious, however, that the practice of living on an inadequate supply of internal funds is not limited to concerns for which it is unavoidable. Many with excellent credit and reasonable access to the capital market persist nevertheless in making do with what they have, regardless of an abundance of replacement opportunities advantageous at any reasonable charge for the money required. In this case the losses from bad equipment policy are not only avoidable; such losses are certainly indefensible.

Whether the shortage of capital is due to inability to bring in outside funds or an unwillingness to do so, it is likely to be reflected in a dependence of equipment expenditures on the current state of the company's treasury. This brings into relevance the returns from another inquiry in the Institute's survey of equipment manufacturers, which has already been cited.

Ques.: To what extent is the customer's current liquid position a factor in his decision to buy or not to buy your product?

	Per Cent of Replies[1]
Determining or important	82
Minor consideration or of no consequence	18

While the very general dependence of equipment buying on current liquidity indicated here cannot be taken exclusively as evidence of undercapitalization, the significance of the showing being obscured in part by other factors, it does suggest very strongly that insufficiency of capital plays a major role.[2]

Here again the failure of management must be ascribed in part to ignorance. Without a reasonable measure of the losses from deferred replacement, the cost of undercapitalization may be obscured and the natural disinclination to engage in outside financing may govern by default.

CONCLUSION

Whatever the relative importance of ignorance, poor organization of equipment policy, lack of capital, and bad analytical devices, their joint result is an average level of replacement policy in American industry that is, to say the least, unsatisfactory. This does not imply, of course, that substandard practice is universal. Many companies pursue a very aggressive policy in this field, and it is not improbable that some of them actually overdo it. Nevertheless the average is low.

In view of the essentially intuitive character of replacement decisions as now conducted, it is not surprising that there is often an amazing diversity of practice even among enterprises engaged in substantially similar operations. This is a fact

[1] Total number of replies, 126.

[2] The most important of the complicating factors just referred to is the possibility of some positive correlation between the current liquid position of the customer companies and their current rate of operation. If by reason of this correlation low liquidity is associated with a reduced *need* for new equipment, including replacement equipment, the curtailment of buying which accompanies low liquidity can be explained in part by this factor, hence is not, to this extent, an evidence of undercapitalization.

which all competent judges attest, including the Bureau of Internal Revenue. We can illustrate by the most recent study to come to our attention, a survey by a trade association in the industrial equipment field of the life expectancies used by its members for income tax purposes on 47 specified items of manufacturing equipment. The average of the highest expectancies reported for these 47 items was 25.4 years; the average of the lowest, 8.6 years.[1] While the service lives approved for tax purposes are by no means an exact reflection of the actual lives, the parallelism is sufficiently close to make this picture broadly indicative. Certainly the range of practice is extremely wide.

The range is typically so wide, indeed, that it is impossible to rationalize it by invoking differences in operating conditions. Unless the more aggressive managements are wrong, the laggards are paying for their slow equipment turnover in lost profits or in avoidable losses. We do not believe that in general the aggressive ones are wrong; on the contrary, we doubt if even the best practice (with occasional exceptions) goes far enough. But even if it does so, it only confirms the backwardness and inadequacy of the general run.

We need not subscribe unreservedly to the common belief of equipment salesmen that their customers' plants are full of replacement opportunities that will yield a pay-off of 2 years or less. This may reflect some degree of exaggeration. But if we define undersaturation of replacement as the continued use of equipment having an adverse minimum higher than that of its best alternative, we can conclude nevertheless that it is widespread and chronic. The opportunities for profitable remechanization are correspondingly great.

[1] The tabulation covers 13 companies.

Chapter XV

DYNAMIC EQUIPMENT POLICY

It may seem strange at first glance that we have employed a title as broad as Dynamic Equipment Policy for a study dealing wholly with replacement. This title is not really a misnomer, however. For if industry suffers from obsolete and inefficient mechanization, this is not due primarily to bad policy in the choice of *original* equipment—*i.e.*, the equipment of new or expanded plants; it is due rather to bad policy in the timing of replacements in existing plants. Obsolete mechanization is first and foremost the result of a degenerative process which develops with the aging of the industry or the establishment affected. It is a disease of maturity.

THE BRITISH EXAMPLE

We can illustrate by reference to the experience of Great Britain, analysed in an earlier pamphlet of the Institute, from which we quote:

> So far as we may judge from the territory surveyed by the working parties and others, it is safe to say, with only slight risk of exaggeration, that Britain knew how to build great industries but never learned how to rebuild them. At their inception, they were the last word in modernity and efficiency, a model to the world. But they became decrepit with age. What happened was a failure of *re-equipment* policy.
>
> No live industry can keep abreast of technology without continuous renewal and transformation of its productive facilities. Existing equipment must be kept on the defensive, compelled always to justify its tenure against the challenge of currently available alternatives. If it fails to meet this challenge it must be displaced, regardless of its age or condition, regardless, therefore, of whether it is physically "worn out." A re-equipment policy that fails to give full recognition to obsolescence is bound to lead to bad mechanization and inefficiency.

The contrast between original equipment policy and re-equipment policy, so conspicuous in Britain, is by no means wholly lacking in the United States. It is, indeed, fairly common to find long-established enterprises using facilities they would not dream of accepting as a gift if they were going into the business in the first place. In that event, they would probably purchase new equipment all around. If their present policy is correct, however, they should equip a new business by scavenging the mechanical graveyards for cadavers similar to those they now employ.

The failure of the re-equipment process in many British industries, and its admitted inadequacy in many cases in the United States, point up the need for a rational policy on the matter in both countries. For in both, new "replacement" installations, despite the deficiency just noted, are normally two to three times the "expansion" installations. This emphasizes the cardinal importance of a sound replacement policy.[1]

THREE REQUISITES OF SOUND REPLACEMENT POLICY

As the preceding chapter makes clear, a sound replacement policy does not arise spontaneously or automatically. First of all, it requires a *rational analytical framework* for the comparison of mechanical alternatives, in other words, a reasonable test of replaceability. Secondly, it requires *proper organization*. This means that the responsibility for keeping abreast of current developments and for bringing reequipment proposals to a decision by the appropriate officials must be in the hands of a competent individual or staff with sufficient time to do the job. Finally, it requires a *proper attitude* all along the line, including the top officials or the board of directors, as the case may be, who make the final decision. This means a willingness to spend money—and to raise it if need be—for justified reequipment.

We have no pet scheme or prescription for the organization of equipment policy. As we pointed out previously, a setup appropriate for a small concern will not be suitable for a large one, nor will it necessarily be the same for different operations of comparable size. We can only emphasize the importance of a competent and continuous study of re-

[1] *Technological Stagnation in Great Britain*, p. 63.

equipment possibilities and leave it to management to work out the organizational details as the individual situation warrants.

As for the stodgy and unprogressive attitude toward replacement frequently encountered among top executives and boards of directors, we know of no cure except enlightenment. For as we indicated earlier, the prime cause of such backwardness is ignorance. We can be reasonably sure that where bad equipment policy is not attributable to a prohibitive shortage of capital it reflects the fact that management simply does not know what good policy is, and is shooting in the dark.

This is where the first requisite of sound equipment policy comes in—a rational analytical framework for the comparison of mechanical alternatives. This is also where the present book comes in. For its main purpose is to supply such a framework.

FURTHER COMMENTS ON OUR METHOD

The replacement procedure we have presented here accomplishes three things: (1) It provides a definite and explicit pattern of assumptions as to the future where assumptions rather than actual estimates are necessary. (2) It insures that the relevant estimates will be made. (3) It so applies these estimates that they yield the right replacement signal *if they (and the accompanying assumptions) are correct.*

We have no desire to claim too much for this procedure. Certainly it is no cure-all for the trials and tribulations that beset the replacement analyst. No standard method, whatever its merits, can encompass the infinite variety and complexity encountered in practice, nor can it be a substitute for sound judgment. Since the analysis is in the nature of the case a rough-and-ready operation compounded of assumptions, estimates, guesses, and hunches, no general prescription can provide more than a guide to judgment. This is as true of our own as of any other.

We have repeatedly emphasized that the procedure can

yield in practice only a first approximation to the solution desired. It provides a guidepost or point of reference. Since it is based—necessarily, as we have seen—on certain standard assumptions as to the future, it gives a result correct only when these are valid. This result the analyst may wish to shade one way or the other in accordance with his judgment as to the appropriateness of the assumptions to the case in hand. He may wish to shade it for other reasons. But at least he knows what he is doing. He can proceed deliberately, and with his eyes open, from a recognized point of departure. We submit that this is better, on any count, than floundering around in total darkness.

SHADING THE RESULTS

It is impossible, of course, to consider, or even to enumerate, all the circumstances and combinations of circumstances that may lead the analyst to modify the results obtained by the application of our standard procedure. All we shall do is suggest a few factors by way of illustration only. The first is the future trend of prices.

FUTURE PRICE TRENDS. Since our procedure is based on present prices—for the challenger, for the defender (salvage value), and for the various elements that enter into the reckoning of next-year operational differences—it takes no cognizance of *future* price changes. It assumes, substantially, that the present price level will continue.[1] While it is no different in this respect from any other replacement formula or procedure we know of, it does leave the analyst with the necessity for some adjustment of the results to allow for anticipated price trends—provided, of course, he feels that he can prejudge these trends with sufficient assurance to warrant the adjustment.

We venture to say that in the great majority of cases the analyst has no views on future price changes firm enough to bank on and that when he does have them, these views are

[1] This expectation is implicit in our standard assumption that future challengers will have the same adverse minimum as the present one. It is implicit also in the assumption that the present challenger's inferiority accumulation will be at a constant rate.

little more than a hunch that the trend will be up or down. His problem, therefore, is to adjust in accordance with this hunch the replacement indications derived from a formula that assumes that prices will move sidewise. While the *direction* of this adjustment is clear (if prices are going up, replacement should come somewhat earlier than the formula indicates; if they are going down, it should come somewhat later), the *amount* is highly problematical. Unless the analyst is willing to project a specific pattern of price changes into the future and to compute the consequences of this projection for the analysis —a difficult if not impossible undertaking—he winds up by hunching the allowance for a price trend that is also hunched. The uncertainty of this adjustment only emphasizes the importance of having a good bench mark or starting point from which to make it; hence it tends to emphasize, rather than to disparage, the value of our basic formula.

FUTURE OBSOLESCENCE. Let us take another example. Our second standard assumption premises a constant rate of inferiority accumulation by the current challenger. While this assumption is made necessary, as to the obsolescence component of inferiority accumulation at least, by our inability in most cases to predict the pattern and timing of future technological improvements, there are instances in which the analyst does have a limited prevision and is able to foresee, dimly at least, the form of impending developments. If there is something in the offing that promises a challenger say a year or two hence that is superior to the present one by much more than the assumed inferiority gradient of the latter would indicate, the results of our procedure should be shaded toward a retention of the defender pending the availability of the future challenger. If, on the other hand, the challengers of the near future promise to be superior to the present one by less than its inferiority gradient assumes, the results should be shaded against the defender.

FUTURE OPERATING RATE. Under our procedure the rate of operation assumed for the challenger is the average or "normal" rate anticipated over a period of years. If the analyst

has enough confidence in his prophetic powers to predict that operations in the early part of this period will be below the assumed average, he can properly shade the results of our formula in favor of the defender. Contrariwise, if he predicts above-average operations in the early years, he can lean the other way.

FUTURE COST OF MONEY. The calculation of the challenger's adverse minimum assumes a constant interest rate (synonymous for this purpose with the cost of money) over the indefinite future. Presumably this rate is the one prevailing currently, or some approximation thereto. Here is another item on which the analyst may venture a more specific prediction if he has enough confidence in his prevision. Suppose that the company is financing the proposed replacement with funds obtained by a bond or stock issue and that a rise in the cost of such funds is anticipated. The results of our procedure will then be shaded in favor of the challenger. If, however, the company is using its own funds and if the analyst expects a rise in the opportunity cost—that is to say, in the return obtainable from alternative investment—he may well shade in favor of the defender.

These are only a few of the possible grounds for shading that may occur in practice, but they suffice to exemplify the character of the process. How much of it the analyst undertakes will depend partly on the size and importance of the replacements he is considering, partly on his own inclinations, partly on the degree to which the standard assumptions underlying our procedure appear inappropriate to the times and circumstances. There is no uniform rule. It may be pointed out, however, that while close attention to probable deviations from the standard assumptions and earnest efforts to appraise the effect of such deviations will undoubtedly improve the analysis in individual cases, they are not likely to make very much difference in the batting average for a large number of analyses made over an extended period of time. In the long run, the deviations of the actual from the assumed conditions will tend to fall in both directions and consequently

to average out. Certainly too much agonizing over them can be a waste of time.

It is appropriate, while we are on the subject, to emphasize that the problem of shading the formula results is in no way peculiar to our own prescription. For no standard analytical framework or procedure can possibly comprehend the diversity of actual life, and it is preposterous to demand that it should. In this respect our formula is in the same boat with every other.

DOES OUR PROCEDURE ASSUME A DREAM WORLD?

We should like to quote from the comments of a leading authority on replacement analysis who was kind enough to review this book in manuscript:

> Although you have made a clear statement of the "standard assumptions" of your idealized type of replacement situation, you have not given enough emphasis to the many ways in which your idealized situation differs from actual ones. In your idealized world, the services of a machine, or of one of its chain of successors, are required forever. Markets never dry up or decline; changes in product design never terminate the need for the services of a special-purpose machine. Moreover, improvements in the art always proceed at a uniform rate. (This is the only possible assumption under which your "gradient" approach can be used.) If the operating costs during the first year of services of a 1949 model are $50 less than those in the first year of a 1948 model, it is certain that the 1950 model will be $50 better than the 1949 model in its first year of life. There is no hazard that the 1950 model will have operating expenses which are, say, $1,000 below the 1949 model.
>
> In your idealized world, no such sudden obsolescence can ever occur. It is a world in which the purchaser of equipment is guaranteed against the occurrence of all contingencies, the prospect of which might make it reasonable to use a safety factor of some sort in his replacement economy studies. It is therefore easy to prove, as you have done, that in your idealized world it is unwise for purchasers of equipment to apply any such safety factors. It does not follow at all that purchasers of equipment in the actual world are unwise to use safety factors.
>
> There are many other points of difference between the idealized world in which the "gradient" approach is appropriate and the

actual world in which replacement decisions must be made. In your world, price levels never change, salvage values always follow a predetermined pattern; it never happens that resale values are particularly favorable in one year and particularly unfavorable in another. A challenger costing $5,000 will be followed by an infinite succession of $5,000 challengers. And so forth. In fact, history repeats itself in your idealized world to such an extent that your assumed conditions are almost as unreal as the assumed conditions on which minimum average cost calculations are based. The only new circumstance which has been introduced is uniform annual obsolescence. I do not find any place in the manuscript in which these practical limitations on the "gradient" approach are brought out.

With all due respect for our correspondent, we submit that he has failed to distinguish between what actually happens in the real world and what can be foreseen or predicted. This distinction, absolutely fundamental to the theory of replacement analysis, we first developed in Chap. V under the heading *Retrospect and Prospect.* There we pointed out with reference to the constant inferiority gradient that *viewed retrospectively*, inferiority accumulation is always irregular and is sometimes highly erratic. We emphasized that both deterioration and obsolescence develop unevenly and may occur in a series of spurts with intervals of comparative stagnation between. We stated with equal emphasis, however, that it does not follow from the irregularity of past inferiority accumulation that projections for the future must also be irregular. On the contrary, the more random and unpredictable these variations in retrospect, the more reasonable and necessary it becomes to ignore them in such projections. *In so doing we are not abandoning the real world for an idealized world that does not exist; we are only recognizing the reality of our own limitations as prophets.*

What we have just said about our standard assumption as to future inferiority accumulation is equally applicable to the other standard assumptions, explicit and implicit, that enter into our procedure. They do not imply that the history of actual developments, when the record is in, will coincide

with the pattern assumed in the replacement analysis. As we observed earlier, no standard assumptions could possibly yield such a coincidence. They are simply a generally reasonable framework of projection for a situation in which projections of some kind have to be made and in which the future is not specifically predictable.

Contrary to our correspondent's contention, therefore, we are not trying to solve the replacement problems of an imaginary world where obsolescence never occurs suddenly, where prices never change, where salvage values follow a predetermined pattern, where the function of a machine goes on forever, etc. Neither are we proposing to guarantee the purchaser of equipment against unforeseen contingencies. So far as our standard procedure is concerned, he can allow for such hazards in his estimate of the challenger's inferiority gradient. After applying the procedure, he can make further allowance, if he feels impelled, by shading the results. Having done this, he must bear the consequences himself.

THE PURSUIT OF SAFETY

The reference just made to the risk of unforeseen contingencies raises a question on which we should say a word before closing this discussion. It has to do with the risk involved in making, or not making, a replacement. Let us quote from another reviewer of this study in manuscript:

> If replacement studies indicate a "break even," or if an evaluation of the uncertainties makes it appear that the possibility of loss from replacement is at least as great as the possibility of gain, the change should be deferred. After all, a decision not to replace is only a decision to defer, and whenever the indications change the replacement can be made. But the decision to replace, if carried through, is irrevocable. In other words, the possible loss from a short deferment is frequently not a serious matter whereas the loss from a replacement may be very substantial if it develops that important factors were incorrectly evaluated.

If this is interpreted as an argument for deferring replace-

ments that are on the border line, as tested by a reasonable analytical technique, it is unobjectionable, but if it is construed to advocate a systematic policy of waiting in the interest of safety until replacements are substantially overdue, it requires another look.

It is true that the decision to defer is a short-term commitment, while the decision to replace involves a commitment for an extended period. It does not follow, however, that there is necessarily an advantage in favoring the shorter commitment. If the projections for the challenger are a reasonable appraisal of the future probabilities, there is as much chance that developments will be more favorable than anticipated as there is that they will be less favorable. There is, by the same token, as much chance to gain by a long commitment as there is to lose by it. Since it can be shown that *if the projections made in a series of replacement analyses average out well* the best policy is prompt replacement, this policy is clearly indicated for any company not too short of funds to risk the added investment it involves. A jittery attachment to the minimizing of investment through delayed replacement may be a necessity for some capital-shy concerns, but this necessity must not be made a virtue. We repeat, if the forecasts are right on the average, the most profitable policy is to make replacements when the signal first sounds.

ADVANTAGES OF GOOD ANALYSIS

It will be evident to anyone who has read this book that there is no royal road to replacement analysis. It is intrinsically and incurably a complex operation. We can simplify it by certain standard assumptions as to the future. We can develop approximative short cuts for the full mathematical procedures. But after all is done, the fact remains that a reliable job takes time and effort—more, indeed, than some analysts are accustomed to give to the crude tests of replaceability now in vogue. We believe, however, that the extra effort is well worth while if it emancipates the enterprise from dependence

on folklore and superstition as the foundation of its equipment policy. We are firmly convinced that the rationalization of this policy offers to most concerns an enormous return for the energy and expense involved.

Even when a company has hit, by luck or intuition, upon a reasonably good replacement policy—and there are many such—it still stands to gain something from a knowledge of more reliable analytical methods than it is now using. After all, an accidental conformity to good practice is hardly a solid base on which to rest, nor can it afford much satisfaction to a management interested in a real mastery of its job. It is better to be right and to know why. We have no hesitation, therefore, in commending proper analytical techniques even to those who may be for the moment, and in general, on the beam.

NATIONAL INTEREST IN EQUIPMENT POLICY

We began this book by emphasizing the importance of sound equipment policy from the standpoint of the economy as a whole. We need not traverse this ground again, but it is fitting in closing the discussion to come back for a moment to this all-important theme.

It is well that the individual company can increase its profits and strengthen its competitive position by good mechanization. If this incentive were lacking there would be little hope of progress in the matter. But we must remember that the major beneficiary from an improvement in the general level of practice will not be industry itself; it will be its customers. Most of the gains will be passed along in increased output and lower prices. The paramount interest, therefore, is the interest of consumers: that is to say, of all of us. We are dealing with a problem primarily of national concern.

If this is true in ordinary times when the national interest in the problem has to do chiefly with the improvement of the standard of living, it is doubly true today when we must look not only to our comfort but to our security. The position

of the United States in the postwar world is not only a reflection of its preeminence in production; it is a challenge to the maintenance of that preeminence. We cannot afford to fall behind in the race. Now less than ever, therefore, can we question the urgency, from every standpoint, of the cause to which this book is dedicated: dynamic equipment policy.

APPENDIX TO CHAPTER II

CHART I

As indicated in the footnote to Chart 1 (page 20), the curves there shown are smoothed trend lines drawn through the actual data. The smoothing is justified by the limitations of the samples available and the desirability of eliminating erratic and meaningless deviations from the central tendency. Except for tractors (diagram *C*), for which a straight line was fitted, exponential or hyperbolic curves were found to give the best fit. The results are rough, of course, but reasonably satisfactory for the purpose.

A. LOCOMOTIVES

The diagram for locomotives is based on figures published in *Combarative Costs of Steam Locomotive Repairs by District*, Federal Coordinator of Transportation (Washington, 1935). On page 107 of this study, which covers the period 1927 to 1929, the variations of age and use are tabulated for 7,829 steam locomotives in service in the Western District. These locomotives are grouped by years of age, ranging from 6 to 41 years, and the average number of miles run annually per locomotive is computed for each group. The trend line on the chart shows a backward projection to cover locomotives under 6 years of age.[1]

B. FARM IMPLEMENTS

The diagram shows the trend of a composite index of hours worked in 1941 for 10 kinds of farm implements, classified in four age groups: 10 years and under, 11 to 20, 21 to 30, and 31 to 40 years, the average hours worked by all four groups combined being taken as 100. Data are from the study by A. P. Brodell and J. W. Birkhead, *Work Performed With Principal Farm Machines* (Department of Agriculture mimeograph, May, 1943, p. 14). The composite

[1] Because the report is primarily concerned with repair costs and deals only incidentally with the intensity of utilization, it gives no figures for locomotives under 6 years of age.

index is our own and covers all the implements for which complete data are provided in this study.

C. TRACTORS

We have in this diagram the trend of average hours worked in 1940 by four age groups of farm tractors: less than 5 years, 5 to 9, 10 to 14, and 15 years and over. Data are from A. W. Brodell and J. W. Cooper, *Fuel Consumed and Work Performed by Farm Tractors* (Department of Agriculture mimeograph, March, 1942, p. 11).

D. TRUCKS

The chart shows the trend of average miles run in 1941 by 588,000 trucks classified by model year. We have treated 1941 as the first year of service for the 1940 model, the second year for the 1939 model, and so on. Data are from the comprehensive survey of commercial vehicles in the United States conducted in 1941 by the Public Roads Administration and reported in *Nation-wide Truck and Bus Inventory*, Table TKm. (Information Memorandum 60, Mar. 31, 1944.) The original data for the 1940 model are substantially below the trend, owing to the fact that they represent for some vehicles of this model only a partial year's operation. We have therefore disregarded the 1940 trucks in deriving the trend curve.

Further information on the performance of trucks of different ages is available from other sources and in each case shows a similarly sharp decline in use with increasing age, but the samples are rather small. Unpublished data for 1384 farm trucks underlying the Cornell University Bulletin *Some Facts Concerning Costs of Operation of Farm Motor Trucks* by M. P. Rasmussen and P. S. Williamson, January, 1941, show the following relation between age and mileage in five northern states, July, 1933 to June, 1934.

Age of Truck, Years	*Distance Driven per Vehicle, Miles*
1	10,246
2	7,373
3	6,782
4	5,990
5	5,020
6	4,788
7	3,628
8	2,686
9	3,140
10	2,972

E. TRUCK-TRACTORS

The figures underlying this diagram also come from the *Nationwide Truck and Bus Inventory* (see Trucks, page 244) and represent average mileage run in 1941 by 95,000 vehicles of different ages (Table TTm).

F. TRAILERS

The figures are again from the *Truck and Bus Inventory* (see Trucks, page 244), but their interpretation, according to the explanation given by the Public Roads Administration in its Information Memorandum 82 (page 7) is different from that of the series used for trucks and truck-tractors. In the case of the trailers, the PRA found it impracticable to make an analysis of mileage driven in 1941 for each year model. The table given by the Administration and used by us is said to give average mileage for each age group, *i.e.*, total mileage driven since new divided by the attained age of each year model.

However, experiments with the PRA tabulations for trucks and truck-tractors, where both the "marginal" and the "average" series were published, make it seem probable that the "average" figures if actually interpreted as mileage driven since new divided by age are substantially too low. There is reason to assume, in fact, that these figures, and the trend fitted to them in our diagram for trailers, are fairly close to a correct "marginal" series such as shown for trucks and truck-tractors (mileage run in 1941 by vehicles of different age). The data cover 59,000 semitrailers. (Table ST1 from Series UIGH).

G. BUSES

The Interstate Commerce Commission published in January, 1945, a study by Warner Tufts entitled *Operating Costs of Intercity Motor Carriers of Passengers in 1939.* The distribution shown in diagram *G* refers to vehicles of 25,000 pounds usual maximum gross weight and an average seating capacity of 36.3 passengers (*ibid*, page 6). This class was selected in order to use the largest group of similar units available. The study covers Class I carriers only.

The PRA in its *Truck and Bus Inventory* (see Trucks, above) tabulated data on all classes of intercity motorbuses. While mileage run in 1940 by buses of different ages is not directly reported, we

have computed it from Basic Table BHMR, on file at the PRA. The results follow.

Age of Bus, Years	*Miles Run in* 1940 (*Thousands*)
1	73
2	75
3	57
4	54
5	43
6	39
7	36
8	29
9	29

H. PASSENGER CARS

The distribution shown is the trend of mileage run in a 12-months period during 1936 to 1938 by cars of from 1 to 9 years of age and over. This information, compiled from questionnaires by the highway departments of six states, was tabulated by the Automobile Manufacturers Association and is shown on page 23 of *A Factual Survey of Automobile Usage*, published by that organization.

Other studies of passenger-car usage show a similar decline with age. See R. A. Moyer and Robley Winfrey, *Bulletin* 143, Iowa Engineering Experiment Station, 1939 (page 33), or the report of the experience of the Southern California Telephone Company, published in *The Tax Digest* of May, 1931 (p. 164).

APPENDIX TO CHAPTER V

CHART 2

PART I. REPAIR COSTS IN RELATION TO AGE

All diagrams in this section of Chart 2 show the distribution, by year of service life, of annual averages of repair costs per unit of current use. To eliminate meaningless aberrations, smoothed trend curves were fitted to the annual data.[1] The curves are all of the type $y = k - a \cdot b^x$ (modified exponential trend), which besides giving a good fit over the whole range of observations in each of the eight cases shown has certain properties which commend it on theoretical grounds.[2] As read from this curve type, repair costs per unit of use increase continuously with rising service age but the annual increment declines by a constant percentage ratio. This means that the curve if extrapolated to the right (for higher and higher service ages) asymptotically approaches a constant figure. For average repair costs, this is a plausible assumption.

A. METALWORKING EQUIPMENT

The curve in this case is based on the repair histories of 106 machines in a metalworking plant operated by a member company of the Institute. All these machines were in service in 1945. They were acquired at various intervals over the preceding 30 years. Repair histories were available for the period 1928 to 1945, in terms of dollars per year on each machine.

Lacking a record of hours worked each year by individual machines (and having only hours of productive labor for the plant as a whole), we experienced great difficulty relating repairs to machine hours, and the results are admittedly very rough. Another difficulty arose from the changing composition of the sample from

[1] In one case, as noted below, the mathematical trend was computed from annual points on a free-hand curve.

[2] In this equation x is the year of service. The other symbols are constants, k being the asymptote which y approaches as a limit with the increase of x.

year to year. This had to be solved by the use of link relatives. Another was encountered in the abnormal expansion of repair costs in the war years 1942 to 1945. It was finally decided to exclude these years from the analysis. Still another appeared in the behavior of the figures for the first two years of service life, which appeared generally too high. Consultation with the company disclosed that improvements, and extra tooling and accessories, often added to new machines in the first year or two of service, had been customarily charged to repairs. We therefore excluded these years from the computation, using merely a backward projection of the trend for later periods. The final result is expressed in terms of an index, the repairs of the third year of service being 100.

B. TEXTILE MACHINERY

Here again the trend is derived from data supplied by a member company, in this case for 40 textile mills installed between 1924 and 1931. Repair costs per year were recorded in each case for the first 10 years of service. These costs were then computed as percentages of the original investment in each unit, adjusted, when necessary, for capital additions after installation. As in the case of metalworking equipment, we lacked data on hours worked per machine; hence to derive average repair costs *per unit of service* it was necessary to adjust for fluctuations in activity. This was done from internal evidence. The results are of course rather crude and will stand only a broad reading.

C. LIGHT TRUCKS

The data for this diagram are from the same source as the passenger-car data, described in Sec. G. As in the case of passenger cars, it was necessary to exclude by estimate the nonrepair items in operating costs as tabulated. This was done by reference to detailed cost data on farm trucks for 1933 to 1934, as reported in *Bulletin* 747 of the Cornell Agricultural Experiment Station.

D. INTERCITY BUSES

We have here the pattern of per-mile repair costs, exclusive of servicing charges and tire and tube replacements, on buses of various ages during the month of November, 1940. The trend has been fitted to data for 21,000- to 27,000-pound buses reported in Warner

Tufts' *Operating Lists of Intercity Motor Carriers of Passengers*, Interstate Commerce Commission (January, 1945). The sample embraces 2,368 buses. To put the repair cost level of the intercity bus series on a basis comparable with that of the local bus data described in Sec. H, we have adjusted the ICC data by the index used for the latter. Costs are shown, therefore, on a postwar (1945) level.

Unlike the city-bus data, which give the repair histories of the same group of vehicles, the intercity data present a simultaneous cross section of the repair costs of contemporaries grouped by age. They are subject, therefore, to the qualifications discussed in connection with other cases of this type.

E. LOCOMOTIVES

The trend presented in this diagram has been derived from *Comparative Costs of Steam Locomotive Repairs by Districts*, the mimeographed report mentioned on page 243. The data reflect the repair experience during the three-year period 1927 to 1929 of locomotives then of different ages, not the repair history of an identical group over the service life. They are significant for our present purpose, of course, only as they indicate what that history would be.

Repair costs are computed per "potential horsepower unit" rather than per locomotive mile as such. They relate, in other words, to locomotive miles adjusted for differences in the horsepower of the units concerned. This adjustment, though necessary because of the wide difference in the average size of new and old locomotives, probably gives an upward bias to the data as a measure of the repair expectancy of the newer units per horsepower mile. This bias results from the fact that the older (and smaller) units run many more locomotive miles per "horsepower unit" than the newer ones. Repairs are in part a function of horsepower miles, of course, but they are also in part a function of locomotive miles; hence they tend to be larger when a "horsepower unit" is run out with small locomotives. The bias from this source may be aggravated by a tendency for older units to have higher repair costs per mile than newer ones *of the same size* would have at their age.

Because of these factors we have limited the time span of the diagram to the first 20 years of service, although the Coordinator's data cover a period twice as long. Our trend differs from the straight line fitted by the Coordinator to the data for the sixth to the forty-

first years, a line reflecting, in our opinion, the upward bias discussed above.

F. FARM IMPLEMENTS

The diagram shows a trend fitted to the aggregate of 1936 repair costs per acre for 15 different farm implements grouped by age. The figures have been computed from unpublished material compiled by the Agricultural Experiment Station of Cornell University and made available through the courtesy of J. P. Hertel. The study covers 2,342 implements. As in the case of locomotives, we have here the repair experience of units of different ages at the same time rather than a history of the same units over their service lives. This cross-section analysis can yield only an approximation to the desired result.

G. PASSENGER CARS

Here we have the trend of repair costs, by age of vehicle, for passenger cars operated by the federal government in the fiscal year 1944, as reported to the Bureau of the Budget. The Bureau's reports include, in combination with repairs, the per-mile cost of fuel, oil, washing, and servicing. We had therefore to make an estimated deduction for these nonrepair items, relying for the purpose on sample studies from other sources. Here again, of course, we have a cross section of various age groups, not a service-life history of identical units.

H. CITY BUSES

The underlying material covers 10 groups of buses, 763 units in all, for which repair histories, on a per-mile basis, were made available through the courtesy of a large metropolitan transit company. The original data show monthly costs for body and chassis repairs, and monthly mileage accomplished by each of the 10 groups during their service lives. They include only normal repairs—not servicing, tire and tube expense, or repairs necessitated by accidents. Each group consists of vehicles of a single body-chassis type from a single manufacturer. For the periods covered, the groups do not vary in composition. All units were in service in December of 1945.

Repair costs have been adjusted for changes in the maintenance wage levels of the reporting company but not for changes in mate-

rials prices, for which no appropriate index was available. Since 60 per cent of maintenance costs were direct labor, that percentage of each figure was adjusted by the wage index. The deflated figures were placed on a postwar (1945) basis. The mathematical trend shown was computed from points on a free-hand curve drawn through the data for the 10 groups.

To indicate the dispersion of the original data about our mathematical trends, we present below the average relative deviation for the seven cases in which the trends were derived from such data.

	Average Percentage Deviation from Trend
Metalworking equipment	18.2
Textile machinery	4.5
Light trucks	4.3
Intercity buses	6.8
Locomotives	5.4
Farm implements	13.1
Passenger cars	3.6

Part II. Repair Costs in Relation to Accumulated Use

In the case of local buses, the trend is derived directly from original data relating repair costs to accumulated use. For the other three cases it is obtained indirectly from the trends on repair costs by age, discussed above, and the trends on use intensity by age shown in Chart 1 (page 20). We cumulated annual trend values in Chart 1 to obtain total usage since installation for each year of service age. This permitted us to relate repair costs to those amounts of accumulated use corresponding to various attained ages and thence, by graphical methods, to constant increments of accumulated use.

We referred in the text to the probability that the relation of repairs to accumulated use is a better measure of their relation to age *for our purpose* than the series shown in Part I. The argument follows: As we indicated in Chart 1 (page 20), use intensity of equipment tends to decline over its service life because of successive replacements and the functional downgrading that accompanies them. For this reason, when we relate repair costs per unit of service to *equal* increments of attained age we are relating it to *diminishing* increments of accumulated use. Since we are interested in the

rate at which deterioration accumulates (hence in the rise of maintenance as a component of that rate) during the period *prior to the first replacement* and since use may be assumed to be more or less constant over that period, the rise of repair costs with constant increments of use as shown in Part II of the chart is presumably a better indication of what it would be with constant increments of age before the first replacement than are the data in Part I, which reflect, as indicated, the effect of diminished use intensity due to successive replacements.

APPENDIX TO CHAPTER VI

RELATION BETWEEN THE ADVERSE MINIMUM OF A SINGLE MACHINE AND THE ADVERSE AVERAGE OF A SUCCESSION OF MACHINES HAVING THE SAME MINIMUM

It should hardly be necessary to prove that when we have an indefinitely extended succession of mechanical generations with identical adverse minima, the adverse average of the succession itself is the same as the minimum of a single generation. The proposition is really a truism. However, the proof is as follows:

$$\text{Capital-recovery factor for } n \text{ years} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$\text{Present-worth factor (of an annuity) for } n \text{ years} = \frac{(1+i)^n - 1}{i(1+i)^n}$$

For $n = \infty$, the difference between $(1+i)^n$ and $(1+i)^n - 1$ vanishes; in other words, both $\frac{(1+i)^n}{(1+i)^n - 1}$ and $\frac{(1+i)^n - 1}{(1+i)^n}$ become unity. Hence, we have for $n = \infty$

$$\text{Capital-recovery factor} = i \tag{1}$$

$$\text{Present-worth factor} = \frac{1}{i} \tag{2}$$

If we denote the adverse minimum of a single generation by m, the present worth of this minimum to infinity is $\frac{m}{i}$ [from equation (2)]. Since the capital-recovery factor for an infinite series is i [from equation (1)] the uniform annual equivalent of the series is $\frac{m}{i} \times i = m$.

APPENDIX TO CHAPTER VII

A. DERIVATION OF THE NO-SALVAGE FORMULA FROM THE GENERAL FORMULA

In the absence of salvage values the general formula becomes

$$\text{Life average of operating inferiority} = \frac{g(n-1)}{2} + \frac{c}{n} + \frac{ic}{2}\text{[1]}$$

This yields the approximate adverse average for a service life of n years. Let us call this average u (for uniform annual equivalent). What we want, then, is the minimum value of u. This may be found by differentiating with respect to n, equating the derivative to zero, solving for the n which satisfies this condition, and substituting this value of n in the formula just given.[2]

$$\frac{du}{dn} = \frac{g}{2} - \frac{c}{n^2} = 0$$

$$\frac{c}{n^2} = \frac{g}{2}$$

$$n = \sqrt{\frac{2c}{g}}$$

The value of u itself is found by substituting in the above formula.

$$u_{\min} = \frac{g}{2}\left(\sqrt{\frac{2c}{g}} - 1\right) + \frac{c}{\sqrt{\frac{2c}{g}}} + \frac{ic}{2}$$

which can be simplified into

$$u_{\min} = \sqrt{2cg} + \frac{ic - g}{2}$$

This last expression is the second formula of the text.

The question may arise why a similar formula for the adverse

[1] When g is the annual inferiority gradient, c the acquisition cost, n the number of years in the assumed service life, and i the interest rate (in decimals).

[2] A curve which has a minimum reaches this minimum at the point where its tangent is horizontal (parallel to the x axis), in other words, where the gradient of the tangent (the first derivative, in the language of the calculus) is zero.

minimum cannot be deduced by the correct method, which relies on uniform annual equivalents rather than simple averages. While it is possible in this case to deduce the mathematical relation between the minimum value of u and the three elements c, g, and i, this relation cannot be stated as an explicit formula for this minimum value.

B. RELATION BETWEEN THE GRADIENT, THE ADVERSE MINIMUM AND THE SERVICE LIFE IN THE NO-SALVAGE CASE

Since in the absence of future salvage value the present challenger will become replaceable when its next-year operating inferiority exceeds the adverse minimum of the then-current challenger and since, by our standard assumption, this adverse minimum will be the same as that of the present challenger itself, it follows that the period required for the next-year inferiority to show such an excess, *i.e.*, the correct service life, is obtainable by dividing the annual gradient into the adverse minimum. This division yields the correct life exactly, of course, only when the theoretically correct adverse minimum is used. Employed in connection with the minimum obtained with the short-cut no-salvage formula, it yields slight and inconsequential errors.

C. ACCURACY OF THE NO-SALVAGE FORMULA

The statement is made in the text that this formula determines the challenger's adverse minimum within 3 per cent of the correct figure for all ordinary cases. Two factors affect the error, the interest rate and the ratio of the challenger's annual inferiority gradient to its acquisition cost, this ratio determining the service life at any given rate of interest. Following are the errors at various interest rates and for various gradient/cost ratios.

Gradient/cost ratio, per cent	Percentage error with interest rate, per cent			
	5 per cent	10 per cent	15 per cent	20 per cent
1	2.8	2.2	−0.9	−5.3
2	2.1	2.3	1.1	−1.0
3	1.6	2.0	1.4	0.1
5	0.8	1.3	1.1	0.5
10	0.2	0.4	0.2	−0.2

This tabulation confirms the highly satisfactory performance of the formula from the standpoint of theoretical accuracy.

D. DERIVATION OF SALVAGE VALUES IN TABLE 6

The values in Col. 2 of this table were obtained for any given year by subtracting from \$1,173 the sum of (1) interest on the opening salvage value for the year and (2) operating inferiority for the year. The balance was taken as the *decline* in salvage value during the year. For example, salvage at the beginning of the year 5 is \$2,519. Interest is therefore \$252. Inferiority for the year being \$400, we have \$652 to subtract from \$1,173, leaving \$521 for loss of salvage during the year, and leaving salvage, accordingly, at \$1,998 at the end of the year.

E. ACCURACY OF THE GENERAL FORMULA

We stated in the text that the adverse minimum developed by the general short-cut formula through the application of the cut-and-try procedure is ordinarily within 4 per cent of the theoretically correct figure. The error (when salvage values are effective) is affected by three factors, the gradient/cost ratio, the course of salvage values, and the interest rate.

Unless we assume the course of salvage values to be a definite mathematical function of the challenger's age, it is impossible to derive a formula delimiting the range of possible error. Obviously such an assumption would be too restrictive, since the movement of salvage (relative to the cost of the asset) can be almost anything, even prospectively. We can, however, approximate the limits of error experimentally, by appropriate variations in the assumed conditions.

The effect of these variations is explored first by assuming the course of relative salvage values described in Table 2 of the text, but varying the gradient/cost ratio and the rate of interest, as follows:

PERCENTAGE ERRORS IN CHALLENGER'S ADVERSE MINIMUM COMPUTED BY THE GENERAL SHORT-CUT FORMULA, FOR VARIOUS GRADIENT/COST RATIOS AND INTEREST RATES, ASSUMING THE COURSE OF RELATIVE SALVAGE VALUES SHOWN IN TEXT TABLE 2

Gradient/cost ratio, per cent	Percentage error with interest rate, per cent			
	5 per cent	10 per cent	15 per cent	20 per cent
1	1.5	1.3	−0.8	−4.6
2	−0.3	0.2	−0.4	−1.2
4	−1.9	−3.1	−3.2	−2.1
5	−1.9	−3.1	−3.9	−4.3
10	−1.9	−3.1	−3.6	−4.4

Except for the extreme case of 20 per cent interest, the errors run below 4 per cent.

If we now take the gradient/cost ratio of Table 2 (2 per cent) and the interest rate (10 per cent) and vary the course of relative salvage values so as to signal replacement (1) at the end of 1 year, (2) at the end of 5 years, and (3) at the end of 9 years (as reckoned by the theoretically correct method), we obtain the following percentage errors in the adverse minima yielded by the general short-cut formula for these various salvage assumptions.

Assumed Course of Relative Salvage Values	*Percentage Error in Adverse Minimum Computed by Short-cut Formula*
(1)	−2.9
(2)	−2.4
(3)	0.2

Such empirical tests could of course be multiplied indefinitely, but it is sufficiently evident that the errors generated by the short cut are negligible.

APPLICATION TO TABLE 2 CHALLENGER. It may be of interest to see the general formula applied to the challenger in Table 2 of the text (page 81). The solution will be found on page 258.

It will be noted that the service life associated with the adverse minimum is lower by the short-cut method than by the correct method. The short cut regularly *understates* the best service life. The defect is not serious, however, since it is the adverse minimum we are after, not the service life as such. So long as the short cut yields a satisfactory figure for this minimum, it is immaterial that that figure is associated with an assumed service life somewhat too low.

F. VALIDITY OF THE RULE THAT IF CHALLENGER SALVAGE VALUES ARE NOT EFFECTIVE DURING THE FIRST 5 YEARS OF SERVICE THEY WILL HAVE A NEGLIGIBLE EFFECT ON THE ADVERSE MINIMUM

Since the salvage values of a challenger can be effective in a great variety of ways and degrees *after* 5 years of service even when ineffective during those years, it is necessary in testing the possible impact of such later effectiveness on the adverse minimum to prescribe a definite course for these values to follow. We have chosen two different prescriptions, one moderate, and one so extreme that it may be regarded, for practical purposes, as a limiting case. The moderate prescription assumes salvage values to decline by a con-

DERIVATION OF ADVERSE MINIMUM OF A CHALLENGER HAVING A COST OF $5,000, AN INFERIORITY GRADIENT OF $100 A YEAR, AND SALVAGE VALUES AS INDICATED, ASSUMING NO CAPITAL ADDITIONS AND INTEREST AT 10 PER CENT, COMPUTED (1) BY THE CORRECT METHOD AND (2) BY THE GENERAL SHORT-CUT FORMULA[a]

Year	Operating inferiority	Salvage value (end of year)	Correct method: Uniform annual equivalent for period ending with year indicated[b]			Short cut: Annual average for period ending with year indicated		
			Operating inferiority	Capital cost	Both combined	Operating inferiority[c]	Capital cost[d]	Both combined
	1	2	3	4	5	6	7	8
1	$ 0	$4,200	$ 0	$1,300	$1,300	$ 0	$1,260	$1,260
2	100	3,500	48	1,214	1,262	50	1,175	1,225
3	200	2,900	94	1,134	1,228	100	1,095	1,195
4	300	2,400	138	1,060	1,198	150	1,020	1,170
5	400	2,000	181	991	1,172	200	950	1,150
6	500	1,700	222	928	1,150	250	885	1,135
7	600	1,400	262	880	1,142	300	834	1,134*
8	700	1,200	300	832	1,133	350	785	1,135
9	800	1,000	337	795	1,132*	400	744	1,144
10	900	800	373	764	1,137	450	710	1,160
11	1,000	600	406	737	1,144	500	680	1,180
12	1,100	500	439	710	1,149	550	650	1,200
13	1,200	400	470	688	1,158	600	624	1,224
14	1,300	300	500	668	1,168	650	601	1,251
15	1,400	200	528	651	1,180	700	580	1,280

[a] Figures do not always add exactly because of rounding.
[b] Cols. 7 to 9 of Table 2.
[c] Average of Col. 1 through year indicated.
[d] Original cost ($5,000) minus salvage value in Col. 2, divided by years in the service life, plus 10 per cent of the average cost and salvage.

stant *relative* rate, the rate satisfying the condition that at the end of the fifth year the value intersects the line of indifference (page 99) from *below*. We are therefore assuming values which are ineffective before that point and reasonably effective thereafter.[1] Under this prescription the no-salvage adverse minimum exceeds as follows the minimum with salvage regarded.

Gradient/cost ratio, per cent	Percentage excess of no-salvage adverse minimum with interest rate of			
	5 per cent	10 per cent	15 per cent	20 per cent
1	5.2	3.3	1.9	0.9
3	3.1	2.8	2.3	1.8
5	1.6	1.7	1.5	1.5
10	.0[a]	.0[a]	.0[a]	.0[a]

[a] The excess of no-salvage adverse minimum is zero in this case because with a gradient/cost ratio of 10 per cent the no-salvage service life is under 5 years. By assumption, therefore, salvage values are ineffective throughout the entire life.

Our second prescription, so extreme, we have said, as to be a limiting case, assumes that salvage value at the end of the fifth year of service is on the line of indifference *and that it does not decline at all thereafter*. This assumption is of course fantastically improbable, but it is useful for that very reason. For it exaggerates to the extreme limit the possible effects of post-5-year salvage values on the adverse minimum.

The tabulation on page 260 shows the percentages by which the challenger's no-salvage adverse minimum exceeds its minimum with salvage values regarded, when, as assumed, these values are ineffective during the first 5 years of service and remain constant thereafter at the indifference figure for the end of the fifth year.

It will be seen that even on the extreme assumption used in this test the no-salvage adverse minimum is only moderately above the minimum with salvage value regarded, save in the one case where a very low rate of interest (5 per cent) is combined with a very low

[1] It is mathematically demonstrable that a constant-rate-of-decline curve which has the same point of origin as the line of indifference and which intersects the latter from below at a certain point, keeps above the line of indifference all the way after that point.

gradient/cost ratio (1 per cent).[1] On any reasonable assumption as to the course of salvage values after the fifth year, these margins of difference are much smaller, as our first example indicates. We are justified in concluding, therefore, that *when the challenger's salvage values are not effective during the first 5 years,* the no-salvage adverse minimum gives in general a very satisfactory result.

Gradient/cost ratio, per cent	Percentage excess of no-salvage adverse minimum with interest rate of			
	5 per cent	10 per cent	15 per cent	20 per cent
1	21.4	12.7	7.1	3.9
3	9.0	8.0	6.6	5.2
5	2.9	3.5	3.7	3.5
10	.0[a]	.0[a]	.0[a]	.0[a]

[a] The excess of no-salvage adverse minimum is zero in this case because with a gradient/cost ratio of 10 per cent the no-salvage service life is under 5 years. By assumption, therefore, salvage values are ineffective throughout the entire life.

G. THE UNDER-10-PER-CENT TERMINAL SALVAGE RULE

As indicated in the text, this rule states that if the salvage value anticipated at the end of the challenger's no-salvage service life is under 10 per cent of its acquisition cost there will be in most cases a negligible difference between the adverse minimum yielded by the no-salvage formula and the minimum with salvage values regarded. Note the qualification "in most cases." The rule assumes that the salvage values that would be projected for intervening years in deriving the salvage-value adverse minimum would follow a more or less normal pattern in relation to the terminal value; that is to say, that they would decline at a more or less constant rate, in *relative* terms, down to that terminal figure. We need not argue here that this course of decline approximates the normal expectancy; we need only make it clear that the rule under discussion presupposes it, and that the analyst should therefore not rely on the

[1] The margins of excess shown in the table are reckoned by the theoretically correct method, as distinguished from the short-cut formulas. The use of these formulas yields generally similar results.

rule when his estimates of future challenger salvage values describe a course substantially above the one assumed.

The following table gives the percentages by which the no-salvage adverse minimum exceeds the minimum with salvage values regarded when these values decline at a constant relative rate down to 10 per cent of acquisition cost at the end of the no-salvage service life.[1]

Gradient/cost ratio, per cent	Percentage excess of no-salvage adverse minimum with interest rate of			
	5 per cent	10 per cent	15 per cent	20 per cent
1	4.9	1.8	0.6	0.2
3	6.3	4.3	2.8	1.2
5	7.7	4.5	3.7	2.1
10	9.4	6.2	4.2	2.9

H. DERIVATION OF SERVICE-LIFE FORMULA FOR CHALLENGER'S NO-SALVAGE ADVERSE MINIMUM

We saw on page 254 that under our general short-cut formula for the challenger's adverse average which in the absence of salvage value becomes $\frac{g(n-1)}{2} + \frac{c}{n} + \frac{ic}{2}$—the service life, n, equals $\sqrt{\frac{2c}{g}}$. We have, therefore, $g = \frac{2c}{n^2}$. Substituting this expression for g in the formula

$$\text{Adverse minimum} = \sqrt{2cg} + \frac{ic - g}{2}$$

we obtain

$$\text{Adverse minimum} = \frac{2c}{n} + \frac{ic}{2} - \frac{c}{n^2}$$

This may be written, alternatively,

$$\text{Adverse minimum} = c\left(\frac{(2n-1)}{n^2} + \frac{i}{2}\right)$$

The general short-cut formula regularly understates somewhat the service life associated with the adverse minimum.

[1] The percentages of excess relate to the theoretically correct adverse minima on both sides. The use of the short-cut minima would yield generally similar though by no means identical results.

This is of little consequence when, as usual, we are sounding for the minimum by trying various assumed lives, for so long as the short cut yields a satisfactory figure for the minimum itself, it makes no difference that it is associated with an assumed life a little too short (as compared with what the theoretically correct procedure gives). When, however, we must insert a service life, n, in the derived formula $c\left(\frac{2n-1}{n^2}+\frac{i}{2}\right)$, it is inconvenient to have to allow for this bias by using a life somewhat shorter than the one estimated to be correct. It is easier to adjust the formula itself so that it will approximate the correct adverse minimum on a correct life estimate. This we have done by substituting the expression $i/1.4$ for the expression $i/2$ in the above equation.

The revised denominator, 1.4, has been arrived at empirically. It is the figure which minimizes the average of relative errors in the adverse minima derived by the formula over the ordinary range of cases *when the theoretically correct service life is used.*[1] These errors, using the 1.4 denominator, are shown below.[2]

Correct service life, years	Percentage errors in adverse minima computed by adjusted short-cut formula, with interest rates of		
	5 per cent	10 per cent	15 per cent
5	6.2	4.2	2.8
10	2.9	0.7	−1.3
15	1.4	−1.3	−4.0
20	0.4	−3.0	−6.3

Obviously the formula is accurate enough for any practical purpose.[3]

[1] The range of cases covers interest rates from 5 to 15 per cent and service lives from 5 to 20 years.

[2] They are deviations from the theoretically correct adverse minimum for the case, not from the approximations yielded by the no-salvage short-cut formula.

[3] For those not averse to a more complex formula, we can offer one that is completely accurate:

$$\text{Adverse minimum} = \frac{cni^2}{in + \frac{1}{(1+i)^n} - 1}$$

This requires a table of present-worth factors.

APPENDIX TO CHAPTER VIII

A. SHORT COMMENT ON THE THEORY OF CONVERSION VALUE

We stated in the text (page 119) that the estimation of conversion value involves the theory of secondary replacement. Let us consider the point a little further.

When the present defender may be worth more for some secondary service in the same ownership than it is for resale, it becomes the challenger for this secondary service. The secondary defender may in turn be worth more for transfer than for sale and become the challenger for some other secondary service. It is possible in this way for one primary replacement to generate a whole chain of secondary replacements in which *A* moves to *B*, *B* to *C*, *C* to *D*, etc.

When we ask in such a case for the conversion value of *A*, the primary defender, it is obvious that we have a complex analytical problem. For to be valid for the primary analysis, that value should reflect all the advantages from the secondary transfers made possible by the primary replacement—the transfer of *A* to *B*'s assignment, of *B* to *C*'s, of *C* to *D*'s, etc. It is necessary, therefore, to consider these advantages all along the line, with due regard at all points for the sale or purchase alternatives. Obviously, this is no easy matter.

Not only is the theory of secondary replacement complicated by the problem of multiple transfers; it will be evident on a little reflection that the standard procedure we have developed for computing the adverse minima of challenger and defender in primary replacements is poorly adapted to secondary replacements. For example, this procedure assumes the continuous (or at least annual) availability of challengers for the defender's job. This assumption is reasonable enough in general when, as in primary replacements, these challengers are purchased in the market. The market is always there. But it may not be at all reasonable when, as in secondary replacements, the availability of challengers depends on primary replacements. If the latter occur at irregular and infrequent intervals, the analytical framework must be modified accordingly at

the cost of abandoning our standard assumption—or indeed any standard assumption—as to challenger availability.

There are other considerations which combine to make the theory of secondary replacement more complex, and its application more difficult, than the theory we have been dealing with. Despite the fact, therefore, that the estimation of defender conversion value in primary replacements does bring us face to face with secondary replacement theory, this circumstance alone does not warrant the further exploration of that theory.

B. EFFECT OF IRREGULAR INFERIORITY ACCUMULATION

We observed in the text (page 132) that for challenger service lives of 5 years or more, irregularities in the projected rate of inferiority accumulation usually make little difference in the adverse minimum as compared with the reckoning based on a constant rate, provided the *average* rate is the same in both cases. It is possible, of course, to project variations so extreme that the difference is substantial, but we are speaking of the ordinary range of cases.

To illustrate, we have computed the adverse minima of two challengers, one with a 5-year service life and one with a life of 10 years, assuming (1) constant inferiority gradients, (2) gradients fluctuating in the following patterns:

Year of service	Increase of inferiority over preceding year			
	5-year challenger		10-year challenger	
	Constant increase	Variable increase	Constant increase	Variable increase
2	$500	$750	$150	$225
3	500	500	150	150
4	500	250	150	75
5	500	500	150	225
6	....	....	150	75
7	....	....	150	225
8	....	....	150	150
9	....	....	150	75
10	....	....	150	150

Assuming no-salvage challengers costing $5,000 each, and 10 per cent interest, the variable gradients, which have the same *averages* as the constant gradient for the 5-year and 10-year periods indicated, yield adverse minima that differ by only 4.7 per cent and 2.8 per cent, respectively, from the minima reckoned with the constant gradients themselves.

C. SPECIFIC ESTIMATES OF OPERATING INFERIORITY ACCUMULATION FOR VERY SHORT-LIVED EQUIPMENT

There are in general two methods of deriving specific estimates of inferiority, one depending on the accumulation of historical data, the other on contemporary cross-section analysis. One works primarily with the dead, the other with the living. Let us begin with the first.

FIRST METHOD. When there are adequate records of the course of the operating costs over the service lives of former units similar to the present challenger (or over the expired portion of the service lives of units still in use) it is possible by analysis of such records to build a year-by-year projection of the same elements of cost for the challenger itself.[1] From this projection it is easy to derive the *increase* of these cost factors with age by subtracting the first-year figure from those for later years.

But even if the projections cover *all* age-related operating costs—which they rarely can do—their rise with age is only a part of the challenger's accumulating inferiority, which includes in addition service deterioration not covered by the cost estimates and—more important as a rule—obsolescence. These factors generate no annual historical statistics comparable to operating costs, and the challenger's future inferiority accrual on their account can hardly be projected by this method in "realistic" year-by-year estimates. It is necessary in most cases, therefore, to lump all factors other than the estimated cost increases under a catchall called "other inferiority" and to estimate its accumulation over the life of the challenger on some simple basis, usually by assuming a constant gradient. Thus the first method becomes in practice a hybrid, with specific yearly estimates for certain elements of operating cost and a more conjectural allowance for the balance.

[1] We speak here of a year-by-year projection, but as we indicated a moment ago, the appropriate time unit for a short-lived challenger may be a half-year, a quarter-year, or a month. We shall use a year simply for illustrative convenience.

To illustrate: A utility operates a fleet of standard half-ton trucks on which it has kept maintenance records for many years. Analysis of these records yields an average maintenance expenditure for each successive year of vehicle life which can be used, with appropriate adjustment, as a forecast for the current challenger. Since it appears that maintenance is the only age-related operating cost of consequence (the variation with age in the case of gas and oil consumption being negligible), it is the only item for which specific estimates are prepared.

There are other elements of inferiority associated with increasing age, however. There is the increased risk of breakdowns and lost time for operating crews. Further, the men do not like to drive aged vehicles, and the company does not like to be seen with them. Moreover, later models usually embody certain improvements and refinements which render their service superior, quite apart from the difference in age. Lumping together these and other elements of inferiority not specifically estimated, the company conjectures that they accumulate at the rate of $50 a year. This, in our terms, is the inferiority gradient for these elements.

The company's specific figures for maintenance inferiority are combined below with its constant-gradient figure for other inferiority to yield a total for each year, as follows:

FIRST METHOD

Year of service	Average maintenance cost for year	Inferiority by year of service		
		Maintenance inferiority	Other operating inferiority	Total inferiority
1	$200	$ 0	$ 0	$ 0
2	360	160	50	210
3	580	380	100	480
4	460	260	150	410
5	530	330	200	530
6	650	450	250	700

SECOND METHOD. The second method, as we have indicated, relies on contemporary cross-section analysis. Units *now in use* are grouped by service years, and the groups are then compared, performancewise, with the youngest—that is to say, with the group in its first year of service. From the pattern of inferiorities developed

by this comparison it is possible, with appropriate adjustments, to project the challenger's own inferiority for successive years of service. Unlike the projections reached by the first method, which are specific, at best, only for increases in operating costs, projections derived in this manner can be specific for *all* elements of inferiority. Nothing remains to be hunched on a constant-gradient basis.

To continue with the case of the public utility and its half-ton trucks, suppose the present fleet is grouped by year of service, the average performance of each group being compared with that of the first-year group, *all differences in operating cost and in value of service being taken into account.* The results, let us say, are as follows:

Second Method

Service Year of Group	*Inferiority of Average Performance as Compared with First-year Group*
1	$ 0
2	250
3	425
4	400
5	500
6	750

The two methods will never yield identical results, and the analyst will usually wish, in any case, to make adjustments before they are used to project the inferiority accumulation of the current challenger.

Year of service	Operating inferiority	Salvage value (end of year)	Annual average for period ending with year indicated		
			Operating inferiority[a]	Capital cost[b]	Both combined
1	$ 0	$1,500	$ 0	$675	$675*
2	250	1,100	125	605	730
3	425	800	225	540	765
4	400	600	269	480	749
5	500	400	315	440	755
6	750	300	388	398	786

[a] Simple average of inferiorities in first column.

[b] Computed by the short-cut formula for capital cost, $\frac{c-s}{n} + \frac{i(c+s)}{2}$ assuming 10 per cent interest.

THE SPECIFIC ESTIMATES APPLIED. Suppose the analyst adopts the results of the second method as they stand. Suppose further that new trucks cost \$2,000 and that their future trade-in (salvage) values are estimated as in the table on page 267. What is the adverse minimum?

The adverse minimum of the new trucks is \$675 a year. The old trucks are therefore replaceable whenever the lowest combination of operating inferiority and capital cost they can show for any future period is above this annual rate.

APPENDIX TO CHAPTER XII

A. VARIOUS WAYS OF COMPUTING THE SHORT PAY-OFF

We have discussed in the text two popular methods of computing the short pay-off, with side glances at the procedures advocated by Professors Grant and Norton.[1] These popular methods differ with respect to the inclusion of interest on the investment; otherwise they are similar. Both deduct the salvage value of the defender from the cost of the challenger, requiring the recovery over the pay-off period of the net, or additional, investment rather than the gross. Both reckon the next-year advantage of challenger over defender in terms of the saving in operating costs only. The simpler, and by far the most popular, method signals replacement when this advantage exceeds depreciation (over the pay-off period) on the net investment; the more elaborate procedure signals when the advantage surpasses depreciation plus interest on this investment.

While these are apparently the most popular versions of the depreciation and depreciation-plus-interest methods, respectively, there are numerous variants. Doubtless a complete canvass would develop dozens of them. We have by no means covered the water front in this respect, and the listing below represents only a few that happen to have come to our attention.

1. The investment in the challenger (to be recovered over the pay-off period) is figured net of the salvage value of the defender, but the operating cost saving is figured on a *monthly* basis, yielding (when divided into the investment) a pay-off period *in months*.[2]
2. Operating cost saving is computed by the year, but investment in the challenger is taken gross with no adjustment for defender salvage value, if any.[3]

[1] Further discussed in Sec. B of this Appendix.

[2] H. P. Bailey in *Finalist Briefs for the American Machinist Awards for 1931*, p. 50. Or Carl Endlein, Jr., *Factory Management and Maintenance*, May, 1934, p. 200.

[3] R. E. W. Harrison, *American Machinist*, April, 1931, p. 469. Or E. M. Richards, *Factory Management and Maintenance*, December, 1933, p. 499.

3. Investment is gross, as in (2), but annual cost saving is calculated after subtracting from the operating cost advantage the excess of normal depreciation on the challenger over the present annual depreciation, if any, on the defender.[1]
4. Investment is net, but the annual operating cost saving is computed as in (3).[1]
5. Investment is the cost of the challenger, plus the remaining book value of the defender, minus the defender's salvage value. The annual cost saving is reckoned by subtracting from the operating advantage the yearly interest on this investment.[2]
6. The investment, as in (5), is the cost of the challenger, plus the remaining book value and minus the salvage value, of the defender, but the annual cost saving is reckoned after charging normal depreciation and interest against both challenger and defender, interest being computed for the former on the investment and for the latter on book value.[3]
7. Investment is the cost of the challenger minus defender salvage, but the annual saving is reckoned after including in costs for the challenger both normal (10-year) depreciation and *average* interest on this investment, while charging into the defender's costs normal depreciation and average interest on the *original* investment (as distinguished from present book or salvage value).[4]
8. Investment is the cost of the challenger, minus the salvage value and plus the book value of the defender. From the annual saving in operating cost is subtracted the excess of depreciation on the challenger (assuming a 10-year life) over the existing depreciation charge, if any, on the defender.[5]
9. Investment is the cost of the challenger, plus the book value of the defender, minus the cost, if any, of rebuilding the defender, and minus *annual* maintenance costs on the

[1] Submitted in confidence by a machinery manufacturer.
[2] R. F. Runge, in *Finalist Briefs for the American Machinist Awards*, 1931, p. 38.
[3] Erik Oberg, *Machinery*, March, 1937, p. 429.
[4] M. S. Curtis, in a paper read before the ASME Machine Shop Practice Division, New Haven, September, 1927.
[5] J. C. Wattleworth and G. V. Patrick, *American Machinist*, June 14, 1939, p. 440.

defender. The annual saving is calculated by reference to operating costs alone.[1]

10. Investment is the gross cost of the challenger. The annual cost saving is the saving in operating costs, plus depreciation and interest on the original cost of the defender, minus interest on the excess of the defender's book value over its salvage value.[2]

These ten examples suffice to show the diversity of practice in the application of the short pay-off. Here is variety without rhyme or reason. Each of these methods yields a different timing of the replacement signal, as the reader can see by trying them out on a hypothetical case. Most of them, it will be noted, give a later signal than the two versions of the device discussed in the text, later certainly than the simple, or no-interest, version. Since that version signals far too late with the popular 3-year and 2-year periods, especially with the latter, the users of these even more tardy variants are compounding an error.

Our ten variants exhibit an almost unbelievable confusion of ideas, which a full tabulation would present in even more astounding measure. We have here, surely, a demonstration that most of the short cuts in popular use are theoretical orphans, while some of them border on superstition. It can hardly be denied that some of the procedures described in this Appendix fall in the latter category.

The disparities of method are, moreover, understated, rather than overstated, by the foregoing summary. This is because we have not touched on the variety of procedures used for computing the challenger's next-year operating cost saving. In some cases the only saving counted is in direct labor. At the other extreme are methods which simply assume the saving in burden to be *proportional* to the direct labor saving. In between are any number of variants yielding widely different results. Thus we pile chaos on confusion.

Despite their differences, however, most if not all of these short pay-off procedures are nearer to each other than they are to the minimum-average-cost formula, especially when they are applied over the popular 2-year and 3-year periods. It appears, therefore, that to turn connoisseur of these procedures is to strain at a gnat and

[1] J. R. Weaver, *American Machinist*, Mar. 1, 1933, p. 138.

[2] J. A. Shepard and G. E. Hagemann, in a paper presented to the ASME, Milwaukee, May, 1925, p. 539.

swallow a camel. A very slight difference in the prescribed capital-recovery period can have more influence on the timing of the replacement signal than any other differences likely to occur.

B. THE GRANT-NORTON METHOD

While neither Professor Grant nor Professor Norton is a champion of the short pay-off device as such, both resort to a modified version of it on occasion, namely, when the risk of substantial future obsolescence is present. When they do use it, their procedure shows a rather wide variance from the popular practice. Thus, for example, both advocate the inclusion of interest in addition to depreciation, but apply it to the *average* investment in the challenger over the pay-off period (allowing in this way for the recovery of the investment through depreciation) rather than to the initial investment.[1] Instead of deducting defender salvage value from this *initial* investment, moreover, they charge the defender with the loss of salvage value over the pay-off period, plus interest on the average value.[2] Finally, they compare *average* operating costs of both challenger and defender over the pay-off period, rather than the challenger's average with the defender's next-year costs, or next-year costs on both sides.[3]

A word about this last feature. While it is by no means invariably true that the sum of the defender's next-year operating and capital costs is lower than the annual average obtainable for some longer period and while a checkup is indicated in questionable cases, certainly there is no presumption that the period of the lowest average coincides with the pay-off period imposed on the challenger. Indeed, there is a general presumption that it does not. For if the assumed life of the challenger is limited to say 3 years because of the risk of obsolescence, it is hardly consistent to suppose that the defender, which may be much older than that already, has a *further* useful life

[1] See Eugene L. Grant, *Principles of Engineering Economy*, rev. ed., Chap. 15, and Paul T. Norton, Jr., *The Selection and Replacement of Manufacturing Equipment.* (Bulletin of the Virginia Polytechnic Institute, Vol. XXVII, No. 11, Part 1, September, 1934). Professor Norton appears to reckon depreciation and average investment without regard to possible salvage value at the end of the pay-off period, while Professor Grant generally (though not invariably) takes account of such salvage value.

[2] In line with the difference of practice cited in the preceding footnote, Professor Norton ignores defender salvage value at the end of the pay-off period, while Professor Grant generally regards it.

[3] Professor Norton appears to follow this method consistently whenever the short pay-off is used, but Professor Grant resorts occasionally to a comparison of average operating cost on the challenger with next-year cost on the defender. See, for example, the solution on p. 208 of the work just cited.

of 3 years. Why assume it will be good for 3 more years in order to test whether it is replaceable now?[1]

As we indicated in the text, the popular version of the short pay-off is to subtract the defender's salvage value from the challenger's cost, thereafter disregarding defender capital cost entirely. The Grant-Norton method does not make this subtraction. Instead, it charges the defender with depreciation (loss of salvage value) over the pay-off period, plus interest on average value. As indicated above, Norton disregards salvage value at the end of the period for both challenger and defender, while Grant adjusts for terminal salvage.

If the method were otherwise correct, we should have to approve Grant's rather than Norton's treatment of terminal salvage. But since the selection of the pay-off period (in cases involving the prospect of substantial challenger obsolescence) is essentially arbitrary, it is impossible to say in general which treatment is better.[2] In any event, a comparatively slight variation in the length of the period selected will usually have more effect on the timing of the replacement signal than any difference between Grant's and Norton's procedures, or, indeed, than any difference between these procedures and the more popular version of the short pay-off device. The length of the pay-off has so controlling an influence that concern over refinements of method seems misplaced.

C. SUBTRACTION OF DEFENDER SALVAGE VALUE FROM THE COST OF THE CHALLENGER

We showed in the text (page 199) that the practice of subtracting defender salvage value from the challenger's cost when used in conjunction with the short pay-off method may influence the result either way as compared with the theoretically correct procedure of charging the defender with its own capital cost (next-year loss of salvage value plus interest on the opening value). All this says is that when one incorrect procedure is combined with another (the short

[1] The usual practice of testing for one more year is justified by the convenience of using annual data, and by the fact that as a rule replacement analyses are not made oftener than once a year. Obviously, if the next analysis will be 3 years hence, it is appropriate to consider that period of additional defender service. But certainly this is not assumed by Grant and Norton.

[2] When the period is too short, Grant's treatment is presumably superior (since the recognition of terminal salvage value will ordinarily reduce the challenger's average capital cost more than the defender's); when the period is too long, the presumption favors Norton's.

pay-off) it may or may not make it worse. What we want to do now is to consider the correctness of this treatment of salvage value in conjunction with our own method of replacement analysis.

Our treatment of salvage value, as the reader will recall, includes in the defender's adverse minimum its next-year *loss* of salvage, plus interest, and excludes from the challenger's adverse minimum the uniform annual equivalent of its own salvage at the end of the period associated with the minimum. Thus it takes cognizance (1) of the next-year *change* in the defender's salvage and (2) of the future salvage (and changes therein) of the challenger. The treatment under criticism ignores both of these factors, however. In subtracting *present* defender salvage value from the challenger investment, it excludes the influence of any *change* in such value during next year (or during a longer period if the defender's adverse minimum is associated with such a period), while in subtracting the defender's rather than the challenger's salvage value, it entirely excludes the latter from consideration. We can state the proposition otherwise by saying that this treatment takes no cognizance of *future* salvage values on either side of the comparison.

It hardly needs emphasis that a method of replacement analysis which ignores future salvage values is bound to yield erratic results. It gives the same adverse minimum for the defender when it has a heavy next-year loss of value as when its value is constant. It shows the same adverse minimum for the challenger when it has substantial future salvage as when it has none. In no case, save by accident, does it yield the correct figure.

To show how improbable it is that the procedure will be right by accident, we may describe in the form of an equation the conditions that must be satisfied for it to yield the same replacement signal as our own formula. Let us first take a case where the challenger has no salvage value after installation. Here the two procedures signal at the same time when

$$\left.\begin{array}{l}\text{Loss of defender sal-}\\\text{vage value next year,}\\\text{plus interest on pres-}\\\text{ent value}\end{array}\right\} = \left\{\begin{array}{l}\text{excess of (1) the challenger's}\\\text{adverse minimum reckoned with}\\\text{gross investment, over (2) its}\\\text{minimum reckoned with gross in-}\\\text{vestment minus defender salvage}\\\text{value}\end{array}\right.$$

If the challenger does have future salvage value, the procedures signal together when

$$\left.\begin{array}{l}\text{Loss of defender sal-}\\ \text{vage value next year,}\\ \text{plus interest on pres-}\\ \text{ent value}\end{array}\right\} = \left\{\begin{array}{l}\text{excess of (1) the challenger's}\\ \text{adverse minimum reckoned with}\\ \text{gross investment, less the present}\\ \text{worth of terminal salvage value,}\\ \text{over (2) its minimum reckoned}\\ \text{with gross investment, minus pres-}\\ \text{ent defender salvage value}\end{array}\right.$$

We can illustrate the first case by the challenger in Table 1 (page 78), assuming that the defender's present salvage value is \$1,000 and that this value will decline \$200 next year. Subtraction of \$1,000 from the challenger's cost of \$5,000 reduces its adverse minimum from \$1,173 to \$1,021.[1] This reduction of \$152 compares with a reduction of \$300 in the defender's adverse minimum through the omission of its next-year capital cost (\$200 loss of salvage, plus \$100 interest). Given the present defender salvage value of \$1,000, equation (1) can be satisfied only when the next-year loss of salvage is \$52.

The second case can be illustrated by the challenger in Table 2 (page 81), assuming the defender just described. Subtracting \$1,000 from the challenger's cost of \$5,000 (and disregarding its own future salvage value) we obtain again an adverse minimum of \$1,021.[2] This is \$111 lower than the correct figure of \$1,132. To satisfy the second equation it is necessary that the defender's next-year loss of salvage be only \$11.

Suppose, again, the defender has a present salvage value of \$3,000 instead of \$1,000. Subtraction of this from the acquisition cost of \$5,000 leaves our Table 1 and Table 2 challengers with an adverse minimum of \$673, against correct minima of \$1,173 and \$1,132, respectively.[3] To satisfy the first equation the defender must have a next-year loss of salvage of \$200; for the second equation it must have a loss of only \$159.

We need not multiply examples. The reader can develop his own if he wishes to pursue the matter further. Suffice it to say that the practice of subtracting defender salvage value from the cost of the challenger is without rational justification. The result of this practice has no systematic relation to the correct one.

[1] Shortening the service life associated with the minimum from 12 to 11 years.

[2] The service life associated with the minimum is lengthened from 9 to 11 years.

[3] The new minimum is for a service life of 7 years, against 11 and 9 years, respectively.

APPENDIX TO CHAPTER XIII

A. VARIOUS FORMS OF THE RATE-OF-RETURN REQUIREMENT

While the version of the rate-of-return requirement analysed in the text is the simplest, and probably the most widely used, there are many variants, of which we have compiled a few for the bewilderment, and perhaps the amusement, of the curious reader.

We should say by way of preface to the listing which follows that what we have referred to in the text as the defender's next-year operating inferiority is usually described in practice as "the annual cost saving." The practical measurement may or may not embrace all elements of defender inferiority (or challenger advantage). To the extent that it ignores differences in the value (as distinguished from the cost) of the service rendered, the method is biased (in addition to its bias otherwise) toward delayed replacement.

1. Investment in the challenger taken net of defender salvage value. Return 15 to 20 per cent on initial investment. Annual operating advantage reckoned on next-year basis. Assumed challenger service life more or less approximating actual life expectancy. (Text version)[1]
2. Same as (1) except that assumed challenger service life is 5 years, far less than actual expectancy for the class of equipment involved (machine tools). Required return is 20 per cent.[2]
3. Challenger investment is gross. Required return not specified. Depreciation (apparently) spread over normal service life. Annual cost saving reckoned after charging both defender

[1] An example of this version, save that it computes next-year "cost saving" rather than operating advantage more broadly may be found in an article by Carl Endlein, Jr., "Should I Buy Special Machines?", *Factory Management and Maintenance*, May, 1934. He gives the challenger a 10-year depreciation period and requires a 20 per cent return on initial net investment.

[2] The challenger's operating advantage is described as "usable cost savings." H. P. Bailey, "Selecting New Equipment to Produce Net Profits," *Machinery*, May, 1933.

and challenger with "burden." Return figured on initial investment.[1]

4. Investment is cost of challenger, plus book value and minus salvage value of the defender. Required return not specified. Challenger depreciation (apparently) at normal rate. Annual cost saving computed after charging defender with present depreciation. Return figured on initial investment.[2]
5. Investment is cost of challenger, plus book value and minus salvage value of the defender. Required return not specified, Challenger depreciation spread over full service life. Annual cost saving reckoned after charging both challenger and defender with average interest on investment (book value for defender) and after charging defender with depreciation (determined by spreading book value over estimated remaining life). The formula

$$\text{Return} = \frac{\text{annual saving—challenger depreciation}}{\text{investment}}$$

purports in this case to give the return over and above interest on the investment. It is figured on the initial investment.[3]

6. Investment is the gross cost of the challenger. Required return not specified. Challenger depreciation at normal rate. Annual cost saving is the saving in operating cost, *plus* depreciation and interest on the original cost of the defender, *minus* interest on the excess of the defender's book value over its salvage value. Return computed on initial investment.[4]
7. Investment is gross. Required return not specified. Annual operating cost saving is divided by gross investment to give *gross* annual return (depreciation and net return combined).[5]
8. Investment in challenger (textile machinery) is net of cost of certain collateral items saved by replacement (work-in-process inventory, floor space, employee housing, etc.) but is

[1] R. E. W. Harrison, "Selling From Next-year's Balance Sheet," *S.A.E. Journal*, April, 1931.

[2] J. C. Wattleworth and G. V. Patrick, "When New Equipment Pays," *American Machinist*, June 14, 1939.

[3] Erik Oberg, *Machinery*, March, 1937.

[4] J. A. Shepard and G. E. Hagemann, in a paper presented to the ASME, Milwaukee, May, 1925.

[5] E. M. Richards, "To Buy or Not to Buy Equipment," *Factory Management and Maintenance*, December, 1933.

not net of salvage value of defending equipment. Depreciation on challenger is spread over full estimated service life (25 years). Annual cost saving is reckoned after charging defender with its present depreciation. Required return is 15 per cent or better (on initial investment).[1]

These examples suffice, certainly, to establish the proposition that the rate-of-return method as applied in practice is a thing of infinite variety. If this diversity reflected an appropriate adaptation of the device to particular needs, it could be excused, or even welcomed, but it is all too obvious that it reflects chiefly a confusion of ideas among those who use it. A full tabulation would dramatize this confusion even further.

In this connection, we may repeat an observation made on page 271 on variations in the short pay-off device. It is equally applicable here.

The disparities of method are, moreover, understated, rather than overstated, by the foregoing summary. This is because we have not touched on the variety of procedures used for computing the challenger's next-year operating cost saving. In some cases the only saving counted is in direct labor. At the other extreme are methods which simply assume the saving in burden to be *proportional* to the direct labor saving. In between are any number of variants yielding widely different results. Thus we pile chaos on confusion.

B. THE COURSE OF DEPRECIATION

We observed in the text (page 204) that depreciation is typically more rapid than the straight-line write-off allows for. Since this is a work on replacement, rather than depreciation policy, it is no place for an extended discussion of the theory of depreciation, much less of its practice. We can, however, point out in passing the course of depreciation that is implicit in the assumptions we have made for computing the challenger's adverse minimum. That is all we propose to do in this context.

These assumptions, for our present purpose, are two: (1) Future challengers will have the same adverse minimum as the present one. (2) The inferiority gradient of the present one is a constant. With these and the necessary estimates we can compute (1) what the value of the challenger will be to the owner at any point in its career and (2) what the decline in this value (depreciation) will be between any two points.

[1] Submitted in confidence by an equipment manufacturer.

Suppose we start with our Table 1 (no-salvage) challenger (page 78). Costing \$5,000, it has an inferiority gradient of \$100 a year, an adverse minimum of \$1,173, and a service life of 12 years. Assuming it is the best new machine for the job in hand and that its challenge of the defender is successful, its value to the owner at the beginning of its career is *the present worth of the annual amounts by which its future operating performance exceeds the level of performance at which it becomes replaceable.* Let us call this, for convenience, its "excess performance." Since the machine becomes replaceable when its operating inferiority relative to future challengers equals \$1,173 (the adverse minimum of these challengers), its excess performance for any year is the amount by which its operating inferiority for the year falls short of \$1,173. Similarly, its value to the owner at the beginning of any year is the then present worth of its excess performance from there to the end of its career. The picture is developed in the following table.

Value of Table 1 Challenger to Owner at the Beginning of Each Year, and Annual Depreciation, Assuming 10 Per Cent Interest
(Adverse minimum of future challengers = \$1,173)

Year of service	Operating inferiority of present challenger for year indicated 1	Adverse minimum of future challengers (\$1,173) minus operating inferiority of present one (excess performance of present one) 2	Present worth, at beginning of year indicated, of remaining figures in Col. 2 3	Depreciation for year indicated (decline in present worth during the year) 4
1	\$ 0	\$1,173	\$5,000	\$673
2	100	1,073	4,327	640
3	200	973	3,687	604
4	300	873	3,083	564
5	400	773	2,519	520
6	500	673	1,999	473
7	600	573	1,526	420
8	700	473	1,106	362
9	800	373	744	298
10	900	273	446	228
11	1,000	173	218	152
12	1,100	73	66	66

A glance at Col. 3 will show that the loss of value to the owner is rapid during the early years of service and slow later. At the mid-point of the service life (the beginning of the seventh year) about 70 per cent of the original value is gone. The annual depreciation (Col. 4) tells the same story, the figure for the first year being 10 times the figure for the final year.

The figures in Col. 3 indicate *what the owner of the present challenger could afford to pay for it* at the beginning of each year of service, rather than buy the best new machine available at that time. The reader will note that these figures are the ones shown in Col. 2 of Table 6 (page 98) as the salvage values which describe the line of indifference for the same challenger. They describe this line precisely because they are identical with what the owner could afford to pay for the machine if he did not already have it.[1] When

VALUE OF TABLE 2 CHALLENGER TO OWNER AT THE BEGINNING OF EACH YEAR, AND ANNUAL DEPRECIATION, ASSUMING 10 PER CENT INTEREST
(Adverse minimum of future challengers = $1,132)

Year of service	Operating inferiority of present challenger for year indicated 1	Adverse minimum of future challengers ($1,132) minus operating inferiority of present one (excess performance of present one) 2	Present worth at beginning of year indicated, of remaining figures in Col. 2, plus present worth of $1,000 terminal salvage value 3	Depreciation for year indicated (decline in present worth during the year) 4
1	$ 0	$1,132	$5,000	$632
2	100	1,032	4,368	595
3	200	932	3,773	554
4	300	832	3,219	510
5	400	732	2,709	461
6	500	632	2,248	407
7	600	532	1,841	348
8	700	432	1,493	283
9	800	332	1,210	210

[1] The test of what the owner could afford to pay for the incumbent machine has been advocated for appraisal purposes by Paul T. Norton, Jr. and Eugene L. Grant in "Depreciation Estimates in Appraisals of Manufacturing Equipment," *Transactions of the American Society of Mechanical Engineers*, July, 1942. Unfortu-

sales values and use values are equal, it is a matter of indifference at every point in the service life whether the asset is sold or kept.

Suppose now we compute the value to the owner of our Table 2 challenger (page 81), which adds the complication of salvage value. In this case the value is the sum of (1) the present worth of excess performance over the remaining service life and (2) the present worth of salvage value at the end of that life. For the Table 2 challenger the adverse minimum is $1,132, the service life is 9 years, and terminal salvage is $1,000.

Here again, depreciation starts high and diminishes with time (Col. 4). Obviously, the customary straight-line write-off bears little resemblance to the course of depreciation implied in our standard assumptions. It will be found, indeed, by anyone who wishes to experiment, that the assumptions implicit in straight-line depreciation as to the course of excess performance are nothing short of absurd. The fact is that any reasonable assumptions that can be contrived yield a *declining* rate of depreciation over the service life. This, however, is a matter beyond the purview of the present study.

nately, these authors derive the adverse minimum of the alternative machine by the minimum-average-cost method, which we have found unreliable when future obsolescence is involved.

APPENDIX TO CHAPTER XIV

A. THE MATHEMATICAL RELATION BETWEEN THE CORRECT SERVICE LIFE AND THE CORRECT PAY-OFF PERIOD IN THE NO-SALVAGE CASE

The first step is to deduce the relation, as determined by our method, between the capital cost (c), the inferiority gradient (g), the rate of interest stated in decimals (i), and the correct service life (n). The deduction is easier under the assumption of continuous functions (continuous rather than annual compounding; operating inferiority expanding continuously rather than by discrete annual steps).

At the end of any service period t, operating inferiority is, obviously, gt. Multiplying this by the present-worth factor for continuous compounding, *i.e.*, by e^{-it}, we have

$$gte^{-it} \quad (1)$$

[1]

The present worth of the total inferiority accumulated over some definite service life x (*i.e.*, from $t = 0$ to $t = x$) is

$$\int_0^x gte^{-it}\, dt$$

Working out the integral, this gives

$$\frac{g}{i^2} - \frac{g}{i}e^{-ix}\left(x + \frac{1}{i}\right) \quad (2)$$

We next obtain an algebraic expression for the sum of the capital cost and the present worth of the total inferiority accumulated:

$$\frac{g}{i^2} - \frac{g}{i}e^{-ix}\left(x + \frac{1}{i}\right) + c \quad (3)$$

Multiplying this by the capital-recovery factor for continuous

[1] Where $e = 2.71828 \cdots$, the basis of natural logarithms. For a derivation of the present-worth factor and the capital-recovery factor for continuous functions, see, *e.g.*, R. G. D. Allen, *Mathematical Analysis for Economists*, pp. 232 and 402, Macmillan & Co., Ltd., London, 1947.

functions, *i.e.*, by $i/(1 - e^{-ix})$, we obtain what we may call the time-adjusted continuous-flow average, over the period x, of capital cost and operating inferiority. Denoting this function by u, we have after simplification,

$$u = \frac{ci^2 + g - ge^{-ix}(ix + 1)}{i(1 - e^{-ix})} \tag{4}$$

The correct service life n is that x which corresponds to the minimum value of u. The condition for u to be a minimum is found by differentiating equation (4) with respect to x and equating the derivative to zero:

$$\frac{du}{dx} = \frac{e^{-xi}(gix - g + ge^{-ix} - ci^2)}{(1 - e^{-xi})^2} = 0$$

Simplifying, and writing n for the optimum x thus determined, we get

$$in + e^{-in} = \frac{ci^2}{g} + 1 \;{}^{1} \tag{5}$$

Since the minimum u equals gn, and the correct pay-off period p is defined by $p = c/u_{\min}$, we can substitute and solve for p, obtaining

$$p = \frac{in + e^{-in} - 1}{i^2 n} \tag{6}$$

The formula may also be used for annual functions, replacing e^{-in} by $1/(1 + i)^n$, the present-worth factor for annual compounding. This gives us

$$p = \frac{in + \dfrac{1}{(1 + i)^n} - 1}{i^2 n} \tag{7}$$

Various tests show that for all practical purposes formula (7) has the same degree of accuracy for annual functions that formula (6) has for continuous functions.

[1] The reader is now in a position to verify our earlier statement (p. 255) that under the correct method it is impossible to write an explicit expression for either n or u in terms of the three elements c, g, and i. This is because the unknown variable appears in the equation both in a linear and an exponential term. The reverse problem is solvable, however. If n (or u), g, and i, are the known variables, an explicit expression can be given from the equation for c, and, consequently, for p as well.

GLOSSARY

Adverse average. The sum of the time-adjusted averages of operating inferiority and capital cost for a specific period.

Adverse minimum. The value of the adverse average at its lowest point.

Challenger. The best unit, or group of units, available at a given time for the replacement of the defender.

Conversion value. The value of an asset for alternative use within the same enterprise.

Defender. An asset now in service, whose replacement is being considered.

Effective and ineffective salvage values. Salvage values are effective when they are high enough to affect the challenger's adverse minimum. When not high enough, they are ineffective.

Incumbent. Synonymous with "defender."

Inferiority gap. The disparity, at any point of time, between the operating performance of a machine in service and the best performance obtainable from its current challenger.

Inferiority gradient. The annual rate at which the inferiority gap widens with the passage of time.

Line of indifference. The line, or course, of challenger salvage values below which they are ineffective and above which they are effective.

Operating inferiority. The amount by which the defender is operationally inferior to the challenger.

Primary and secondary replacement. Primary replacement is replacement by a challenger now outside the enterprise. Secondary replacement is replacement by a challenger already within the enterprise.

Service life. The age of an asset associated with its adverse minimum.

Time-adjusted average. Uniform annual equivalent.

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